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Spectroscopic distances to late-type stars

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Abstract. A common approach to determining distances to stars without astrometric information is to compare stellar evolution models with parameters obtained from spectroscopic techniques. This method is routinely applied in the context of large-scale stellar surveys out to distances of several kpc. However, systematic errors may arise because of inaccurate spectroscopic parameters. We explore the effects of non-local thermodynamic equilibrium (NLTE) on the determination of surface gravities and metallicities for a large sample of metal-poor stars within approximately 10 kpc of the Sun. Using the improved $T_{\rm eff}$ scale, we then show that stellar parameters estimated based on the widely used method of 1D LTE excitation-ionization balance of Fe results in distances which are systematically in error. For metal-poor giants, [Fe/H] ~ -2 dex, the distances can be overestimated by up to 70%. We compare the results with those from the Radial Velocity Experiment Survey catalogue (RAVE) for the stars in common, and find similar offsets.

Keywords. stars: late-type, stars: fundamental parameters, stars: distances, Galaxy: stellar content

1. Introduction

Stellar kinematics is a key ingredient in any study of Galactic structure. Direct distances from *Hipparcos* are now available for many thousands of stars. However, their accuracy rapidly deteriorates beyond a few hundred pc from the Sun. For large-scale stellar surveys, such as SDSS/SEGUE (Rockosi *et al.* 2009), GCS (Nordström *et al.* 2004), and RAVE (Steinmetz *et al.* 2006), the only alternative is to resort to spectroscopic and photometric methods, combined with stellar evolution models. Spectroscopic surface gravities have the advantage of being reddening-independent and, contrary to photometric calibrations, can be determined consistently with metallicities and effective temperatures from observed spectra, thus minimizing the total error caused by various sources of uncertainties. Clearly, the nececessary condition is that the models of spectral-line formation in stellar photospheres are sufficiently realistic, so that applying them to observed spectra provides accurate basic stellar parameters.

In the past decades, most spectroscopy of late-type (FGKM) stars relied on simplified models constructed based on the assumptions of local thermodynamic (LTE) and 1D hydrostatic equilibrium (HE). Because the models are still widely used for the analysis of large data sets, the principal question is whether such a 1D LTE approach is viable. Recent observational and theoretial studies revealed substantial systematic biases in basic stellar parameters at low metallicities and/or gravities caused by the breakdown of LTE and 1D HE approximations (e.g., Asplund 2005; Bergemann *et al.* 2012; Ruchti *et al.* 2012)

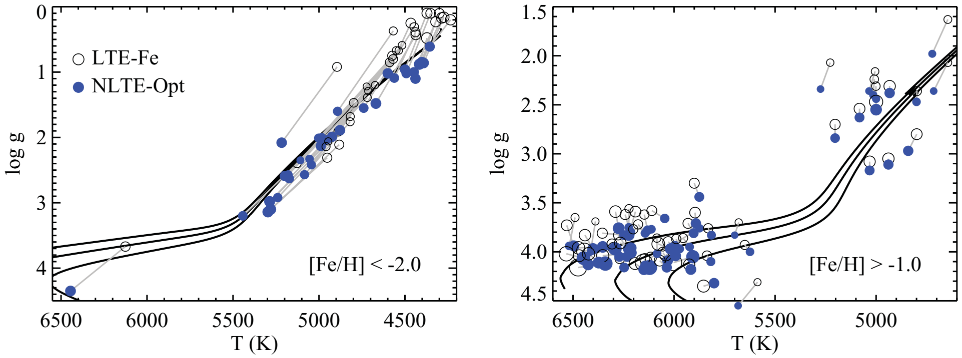

Figure 1. Location of the stars for the parameter sets LTE-Fe and NLTE-Opt in the HRD. Reference stellar evolutionary tracks of 0.8, 0.9, and 1.0 $M_\odot$ and metallicities [Fe/H] = −2.2 (left) and −1 dex (right) are overplotted.

In this paper, we explore the effect of these model shortcomings on the spectroscopic distance determinations using a large sample of metal-poor stars in the Galactic disk. The detailed description of the methods and results will be presented in A. Serenelli *et al.* (2012).

2. Methods

Our stellar sample contains 254 stars in the metallicity range $-3.0 <$ [Fe/H] < -0.5 dex. The stars were originally selected for high-resolution observations based on data obtained by the Radial Velocity Experiment Survey (RAVE; Steinmetz *et al.* 2006) to study the metal-poor thick disk of the Milky Way. High signal-to-noise (S/N) spectra for these stars were obtained by Ruchti *et al.* (2011) using high-resolution echelle spectrographs (spectral resolution $R \geqslant 30\,000$ and S/N ~ 100 per pixel) at several facilities around the world.

Stellar parameters were determined using two different techniques (see Ruchti *et al.* 2012). First, we apply the widely used method of 1D LTE excitation-ionization equilibrium of Fe (LTE-Fe). In the second approach (NLTE-Opt), substantial efforts were made to improve the accuracy of basic stellar parameters in an attempt to minimize the systematic errors. We derive $T_{\rm eff}$ from the weighted averaging of several methods. In particular, the largest weight was usually given to Balmer lines. We then computed gravities and metallicities adopting the new $T_{\rm eff}$ scale and taking into account the NLTE effects in the Fe lines.

The differences between the NLTE-Opt and LTE-Fe stellar parameters are systematic, and they range from −100 K (dwarfs with [Fe/H] $\geqslant -1$ dex) to +400 K (metal-poor subgiants, red giants) in $T_{\rm eff}$, 0.1 to 1.5 dex in $\log g$, and 0.05 to 0.5 dex in [Fe/H]. Fig. 1 illustrates the associated changes in the position of the stars on the Hertzsprung–Russell diagram (HRD).

In addition, we developed a new Bayesian method to determine the evolutionary stage of a star, similar to previous work (e.g., Burnett & Binney 2010). A complete grid of stellar evolutionary tracks was computed with the GARSTEC code (Weiss & Schlattl 2008). The method provides masses, ages, and absolute magnitudes. To determine distances, we used the 2MASS $K_{\rm s}$ magnitudes and reddening values as described in Ruchti *et al.* (2011).

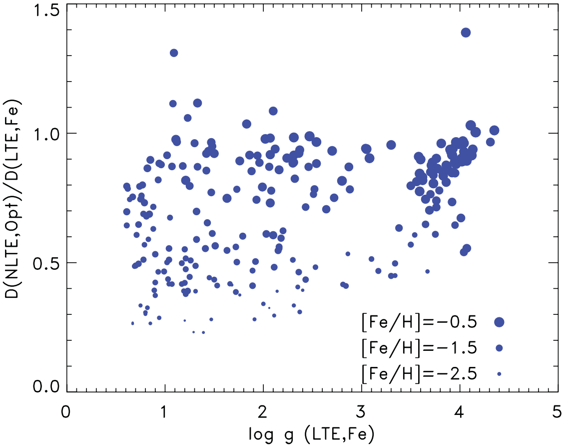

Figure 2. Ratio of distance derive with LTE-Fe and NLTE-Opt stellar parameters as a function of surface gravity for our full sample. Symbol size indicates the stellar metallicity.

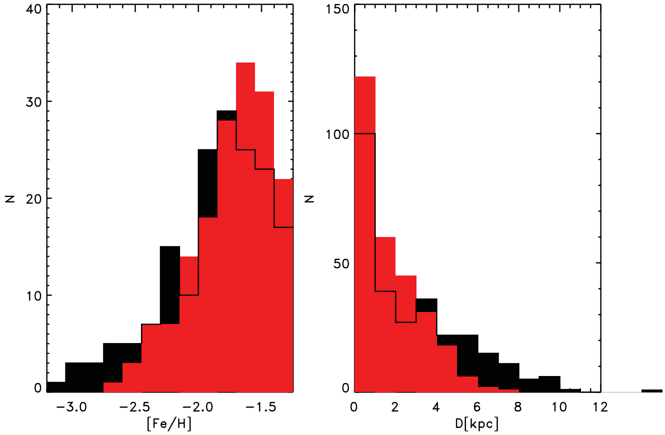

Figure 3. Distribution of stars in our sample as a function of metallicity (left) and distance. The shapes of the distributions are clearly different when more realistic models including NLTE (red) are used to determine the metallicities and distances of stars (compared to LTE, black).

3. Results

In what follows, we briefly discuss our results for distances, while the final distributions for stellar masses and ages will be described in our forthcoming publication (A. Serenelli *et al.*, 2012).

The large changes in gravity have a dominant impact on the luminosity that simply follows from the functional dependence of $\log g$ on stellar radius. With some exceptions representing the more metal-rich solar-metallicity dwarfs, most of our stars are fainter than what one would infer by adopting the LTE-Fe parameters. As a consequence, distances derived from the LTE-Fe set of parameters are usually overestimated (see Fig. 2). For subgiants and metal-poor dwarfs ($\log g > 3.6$) with $[\mathrm{Fe/H}] \leqslant -1$ dex, LTE-Fe parameters imply a systematic distance error of approximately 10–40%. The problems are exacerbated at low metallicity and low gravity. Metal-poor giants suffer from the largest fractional distance biases of 70% (see Fig. 2).

To illustrate these effects, we also show the distribution of stars in our sample as a function of metallicity (left) and distance (right) in Fig. 3. For clarity, only the stars with

[Fe/H] < -1.5 dex are shown. Because of the sample selection effects, these histograms should not be seen as representative of the true shape of the metallicity distribution function in the thick disk. However, they do offer an important insight into how the improvements in the physics of radiative-transfer models for stellar atmospheres, and thus input stellar parameters, would affect these distribution functions. In a magnitude-limited survey (such as RAVE), where more metal-rich, unevolved stars dominate the nearby sample and metal-poor luminous giants are predominantly observed at larger distances, classical LTE-Fe analysis will systematically overestimate distances, placing stars progressively farther than they are. This would cause the unphysical smearing of the metallicity distribution function (Fig. 3, black area), as well as the stretching of the distance scale. Clearly, the effects will be more prominent for metal-poor stars.

A comparison of our parameters with those from the RAVE DR3 (Zwitter *et al.* 2010) for the stars in common reveals significant systematic differences. Their $T_{\rm eff}$ and $\log g$ values are lower for metal-poor giants, but higher for metal-rich dwarfs. As a result, our distances for giants and/or metal-poor stars are smaller than derived from the RAVE DR3 data by 10–50%; on the other hand, we favor larger distances for the nearby dwarfs. This suggests that RAVE DR3 stellar parameters are affected by the systematic error caused by the 1D LTE assumption in spectroscopic parameter determinations. The near-IR lines of Fe I and α elements (Si I, Mg I, and Ti I), which dominate the RAVE spectra (Zwitter *et al.* 2008, their section 4.2.3) all form in NLTE (Zhao & Gehren 2000; Shi *et al.* 2011; Bergemann *et al.* 2012b) and it is unlikely that the NLTE effects cancel out to produce a spectrum close to LTE.

In summary, we have demonstrated that basic stellar parameters for late-type stars derived using Fe I lines and 1D LTE radiative-transfer models result in spectroscopic distances which are systematically in error. Distances to metal-rich stars, [Fe/H] > -0.5 dex, are slightly overestimated. For metal-poor ([Fe/H] $\leqslant -1$ dex) stars, we find a systematic distance error of 10–70% depending mainly on surface gravity.

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