Laboratory Astrophysics: from Observations to Interpretation
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Laboratory astrophysics for the interpretation of stellar spectra

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Abstract. High-resolution stellar spectra are important tools for studying the chemical evolution of the Milky Way Galaxy, tracing the origin of chemical elements, and characterizing planetary host stars. Large amounts of data have been accumulating, in particular in the optical and infrared wavelength regions. The observed spectral lines are interpreted using model spectra that are calculated based on transition data for numerous species, in particular neutral and singly ionized atoms. We rely heavily on the continuous activities of laboratory astrophysics groups that produce high-quality experimental and theoretical atomic data for the relevant transitions. We give examples for the precision with which the chemical composition of stars observed by different surveys can be determined, and discuss future needs from laboratory astrophysics.

Keywords. atomic data, stars: late-type, techniques: spectroscopic, surveys

1. Introduction

High-resolution stellar spectra play a crucial role for studying the chemical and dynamical structure and evolution of the *Milky Way*, deriving the *origin of chemical elements*, and determining the properties of *planetary host stars*. In recent years, large amounts of data have been accumulating from surveys and individual observing programs, in particular in the optical and infrared wavelength regions. The interpretation of the observed spectral lines using model spectra requires high-quality atomic transition data.

A number of ground-based observational surveys are currently obtaining and processing stellar spectroscopic data on an industrial scale, and several more are planned for the near future. The common goal of these surveys is to provide a homogeneous overview of the distributions of motions and chemical abundances in the Milky Way. The difference between surveys lies in the specific methods and/or objects studied in order to achieve this goal. We give three examples in chronological order, all of which are collecting spectra with a resolution of $\lambda/\Delta\lambda \gtrsim 20\,000$ for 10^5 to 10^6 stars.

The APOGEE survey (Majewski *et al.* 2017, USA), operating at infrared wavelengths (H-band), has been targeting ~150 000 stars with a focus on the dust-obscured parts of the Galaxy. The Gaia-ESO Public Spectroscopic Survey (Gilmore *et al.* 2012; Randich *et al.* 2013, ESO VLT)covers a considerable part of the optical spectral region and was designed to complement the ESA space mission Gaia by obtaining high-resolution spectra for up to 100 000 faint stars. Also the GALAH survey (De Silva *et al.* 2015; Buder *et al.* 2018, Australia) is obtaining optical spectra (for up to 10^6 stars), and has its focus on chemical tagging.

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† and the Gaia-ESO line list group (Karin Lind, Maria Bergemann, Martin Asplund, Paul S. Barklem, Šarunas Mikolaitis, Thomas Masseron, Patrick de Laverny, Laura Magrini, Juliet C. Pickering *et al.*)

2. Line lists

The atomic and molecular data needed for modelling stellar spectra by solving the equation of radiative transfer are usually compiled in a line list for each project. This is a list of (upper and lower) level energies, transition probabilities (often in the form of oscillator strengths or gf-values), and broadening parameters for each transition between two states (corresponding to a spectral line). Transition probabilities are taken either from measurements by laboratory astrophysics groups or from calculations by atomic physics groups. Line broadening is mainly caused by collisions with neutral or charged particles, for which very few experimental data have been obtained, and the majority of which are therefore calculations by atomic physics groups (Barklem 2016).

Data published by different laboratory astrophysics and atomic phsics groups may be extracted directly from the literature, or from databases specialising in different applications. Examples are the NIST Atomic Spectra Database (Kramida *et al.* 2018), the VALD database (Ryabchikova *et al.* 2015), and the STARK-B database (Sahal-Brëchot *et al.* 2017). The Virtual Atomic and Molecular Data Centre (Dubernet *et al.* 2016 and poster number 26 in this conference, VAMDC, http://www.vamdc.eu) is an electronic infrastructure providing access to ∼30 databases simultaneously, both via a web interface (the VAMDC portal) and via various Virtual Observatory tools. When using data from databases care must be taken to include citations to the original literature in publications.

For the stellar spectroscopic surveys mentioned previously, the relevant species are mainly neutral and singly ionized atoms, as well as diatomic and triatomic molecules, as most targets for galactic and planetary studies are F-, G-, or K-type stars.

The line list used in the APOGEE survey (Shetrone *et al.* 2015) comprises ∼130 000 lines for 36 atoms and 6 molecules in the wavelength range from 1500 to 1700 nm, with the “best” atomic data from the literature, and astrophysical atomic data calibrated on the Sun and Arcturus for ∼20 000 lines. Within the Gaia-ESO consortium a large effort has been put into the construction of a line list which is being used as a source of common input data by the up to 14 research groups participating in the abundance analysis of the survey data. The Gaia-ESO line list has also constituted the starting point for the GALAH line list.

In brief, ∼1300 transitions were preselected in the relevant wavelength ranges (475 nm to 685 nm and 850 nm to 895 nm), which were presumed to allow accurate determination of stellar parameters, and of abundances for many elements for FGK-type stars. A compilation of the best atomic data for these lines defined the standard line list, representing 35 elements (44 neutral and singly ionised species). A simple quality flag was assigned to each line, indicating whether the sources of gf-values were accurate recent laboratory measurements (published from the 1980s onwards), less accurate older experimental gf-values, or theoretical data. We emphasise that no astrophysical gf-values were included or derived.

The preselected lines were complemented with available data for all lines in the observed spectral range of the target stars, extracted from the VALD database in the case of atoms, and calculated and compiled by T. Masseron for 12 diatomic molecules. These data are needed to identify blends for the preselected lines, and as “background” for synthetic spectrum calculations. They were used to assign a second flag to each preselected line, according to blending properties.

As an example for an application of the Gaia-ESO line list, Fig. 1 shows observed (Hinkle *et al.* 2000) and calculated spectra for the giant star Arcturus in a small wavelength interval, convolved to the spectral resolution used in the Gaia-ESO survey. Most of the observed features are reproduced by the calculations, but deviations occur in several places. Calculated lines may be too weak or completely missing, or may be too strong

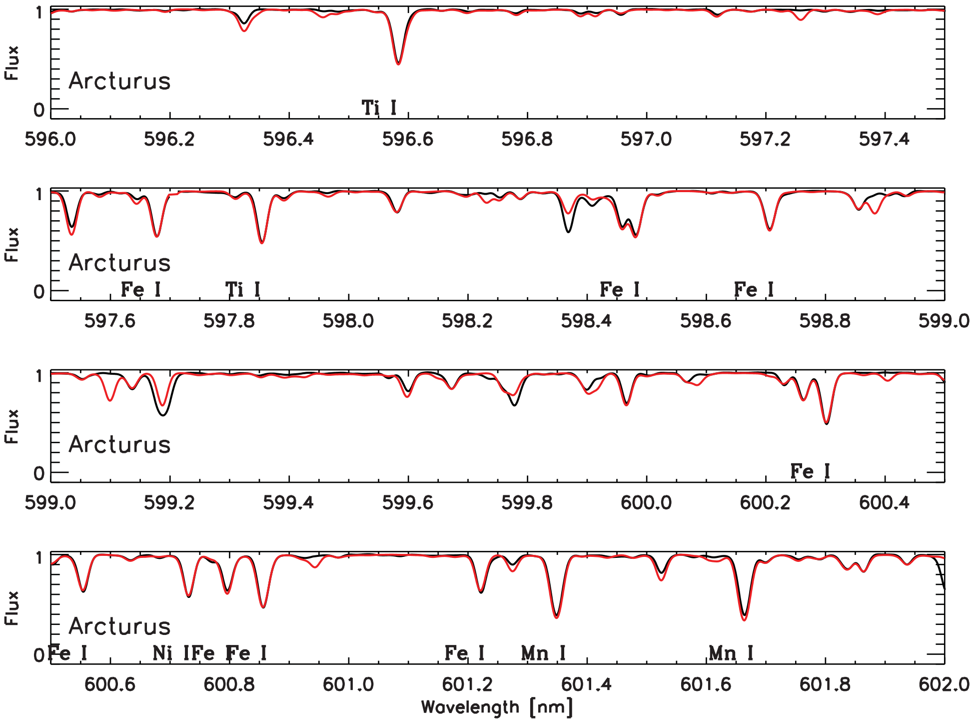

Figure 1. Observed (black) and calculated (red/gray) spectra for Arcturus for a small wavelength interval in the optical region. Some of the strongest lines from the Gaia-ESO line list are labelled by their species.

compared to the observed lines. This indicates deficiencies in the atomic data. An extensive description and discussion of the Gaia-ESO line list is to be found in Heiter *et al.*, (in prep).

3. Abundance precisions and data needs

One way to evaluate the importance and quality of atomic data is to investigate the precisions of elemental abundances achieved by the different surveys. A caveat to this approach is however that the abundance precisions also depend on stellar parameters, analysis methods, and the definition of “precision”. For example, in the APOGEE survey the star-to-star scatter within clusters is used, while the Gaia-ESO survey refers to the method-to-method dispersion or the line-to-line scatter.

Nevertheless, the general picture emerging is that the abundances obtained by the APOGEE survey (Holtzman *et al.* 2015; Mészáros *et al.* 2015; see also Holtzman *et al.* 2018; Jönsson *et al.* 2018) appear to achieve the highest precision (their uncertainties <0.05 dex) for α-elements, Fe, and Ni, and the lowest precision for V. Problems for Al, Ca, and Ti are encountered at low abundances.

Within the Gaia-ESO survey (Smiljanic *et al.* 2014; Mikolaitis *et al.* 2014; Lanzafame *et al.* 2015; Jofré *et al.* 2015) high precision abundances (uncertainties <0.15 dex) can be obtained for up to ten elements, including Al, Si, and Ca, while the least reliable abundances are obtained for Co, Ni, Zn, and Y. There are also problems for V at low metallicities.

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The flags provided with the Gaia-ESO line list may be used to assess future data needs and to compile a wish list for new experimental gf-values in the *optical* wavelength region. Focussing on lines which are more or less unblended, high priority should be given to species which have uncertain transition probabilities for $> 50\%$ of these lines. This concerns ∼240 Fe I lines, ∼50 Ni I lines (whith high excitation energies), and some Fe II, Na I, Si I, and Ca II lines. However, there are a few species for which all of the few available "unblended" lines have uncertain gf-values, and these should be given even higher priority: Al I, S I, and Cr II.

In summary, we emphasise the importance of accurate atomic data in the optical and IR for the interpretation of the data obtained by large-scale stellar spectroscopic surveys. Today, abundances with typical precisions of ∼0.1 dex are being determined on an industrial scale for ∼10 chemical elements. For recent progress in laboratory astrophysics the latest report by the IAU Working Group on High-Accuracy Stellar Spectroscopy (Barklem *et al.* 2018) may be consulted. The line-list work done within the Gaia-ESO survey provides a convenient starting point for the analysis of optical spectra of FGK stars. It also allowed us to identify several elements with urgent need for better atomic data.

This work of comprehensive data compiliation and quality assessment should be extended to the near-IR region in a similar way. Besides the APOGEE survey, high-resolution spectra in the wavelength range from ∼700 to 1400 nm are becoming ever more prominent sources of information about stars, for example in recent studies of the properties of M dwarfs (Lindgren & Heiter 2017; Passegger *et al.* 2018).

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