On the accuracy of oscillator strengths in the near-infrared for the Gaia space mission

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Abstract. We have tested the accuracy of oscillator strengths and wavelengths of some spectral lines (Fe i, Si i, Ca ii) of interest for the Gaia space mission in the near infrared (848-875 nm). The method used in this work consists of fitting synthetic lines calculated using a 3D hydrodynamical simulation of the solar surface with a high-resolution solar spectrum. We found good agreement when atomic data measured in the laboratory were used.

1. Introduction

Gaia is one of the cornerstone missions of the European Space Agency (ESA) dedicated to the study of the Milky Way. It will provide unprecedented clues on the origin and evolution of our Galaxy by performing global astrometric determinations of positions and velocities for billions of objects as faint as visual magnitude V=20 [1]. Gaia is the successor of the Hipparcos mission but is far more ambitious since it will be two orders of magnitude more accurate (25 μas at V=15) and will detect 10^4 times more objects. A great improvement will be the presence of an onboard multicolor photometer and a spectrometer, which will provide information on the nature of the detected objects.

The Radial Velocity Spectrometer (RVS) will collect millions of stellar spectra in the near infrared (848-875 nm) during the mission. This spectral window was selected because of the presence of the strong infrared (IR) Ca ii triplet, visible even in metal-poor stars. The main goal of the RVS is to determine the radial velocities of the stars up to visual magnitude 17. Another important result will be the determination of the chemical abundances with a precision of ~0.2 dex for millions of stars up to magnitude 15, which will be an unprecedented mapping of the stellar abundances throughout our Galaxy.

Atomic data are often the Achille’s heel of stellar abundance and radial velocity determinations. Indeed, the accuracy of these stellar parameters is directly dependent on the accuracies of the central wavelengths and oscillator strengths, gf-values, of the transitions. Unfortunately, only a few transitions are measured in the laboratory in the IR domain. As an example, to the authors’ knowledge, only 10 Fe i lines have measured gf-values within the spectral domain of Gaia. Regarding the challenges and importance of the Gaia mission, we have decided to test the accuracies of both wavelengths and oscillator strengths of the most significant Fe i, Si i and Ca ii lines in the RVS spectral domain. The method consists of fitting these lines to the observed solar lines using an atmospheric model. This approach was used by Thévenin [2, 3], and recently with more modern tools[4], using a state-of-the-art 3D hydrodynamical simulation of the solar surface instead of standard 1D hydrostatic models.
Figure 1. (Left): Snapshot of the temperature inside the simulation box at a representative time. The temperature ranges are about 22000 K at the bottom down to 4500 K at the top of the domain. The emerging intensity is shown on top of the box. The horizontal dimensions are 6 \times 6 \text{ Mm}, and 3.5 \text{ Mm} vertically. The asymmetry between upflows and downflows is visible. (Right): A comparison of a synthetic disk-center intensity (♦) of Si\textsc{i} with the observed solar spectrum (——) [5]. The residual intensity is shown at the bottom. The agreement is better than 1%. From [4], with permission.

The atomic data used in this work were extracted from VALD (Vienna Atomic Line Database\(^1\), cf [6] and Heiter et al. in these proceedings). This database contains laboratory, semi-empirical and calculated oscillator strengths with various accuracies, which are tested in the present paper.

2. The 3D hydrodynamical atmosphere and line formation

2.1. The 3D solar atmosphere

The numerical code used for this work has been developed for the study of solar and stellar granulation [7, 8, 9] and line formation, e.g. [10]. It solves the non-linear, compressible equations of mass, momentum and energy conservation on a Cartesian mesh. It uses the realistic equation-of-state and opacities of the MARCS code [11] and updates [12]. To account for line blocking, we use the most recent ODF [13]. The radiative cooling/heating is obtained by solving the local thermodynamic equilibrium (LTE) transfer equation at each time step along several rays inclined to the surface normal. The line-blanketing is taken into account through the opacity binning technique [7]. A horizontal periodic boundary condition and transmitting vertical boundaries are used. Neither magnetic field nor chromospheric effects are taken into account.

We have obtained time-dependent 3D models of the surface layer of the Sun, as illustrated in Fig. 1. The model is defined by the effective temperature \( T_{\text{eff}} = 5780 \pm 20 \text{ K} \), the gravity \( \log g = 4.44 \) and solar chemical abundances [14]. We note that the effective temperature is not an input in our model but rather an output fluctuating around a mean value. The input that defines the amount of heat injected into the model is rather the entropy at the base of the simulation box. The time sequence spans several hours, enough to cover several convective turn-overs. We used a grid at a sufficiently high resolution, \( (x,y,z) = 253 \times 253 \times 163 \), to get accurate line profiles (cf [15] for more details).

\(^1\) http://ams.astro.univie.ac.at/vald/
2.2. Line formation

From the radiative hydrodynamical simulation we extract a run of 1 hour, with snapshots stored every 5 minutes. For each of them, the radiative line transfer was solved with long characteristics using a modified Feautrier scheme [16]. Pure LTE (no scattering) is assumed. The disk-center intensities (i.e. vertical emerging intensities) are computed for each grid point at the surface. We use the most recent quantum mechanical calculations of hydrogen collisions with neutral species [17, 18, 19], which is a great improvement compared with the traditional Unsöld recipe since we no longer need an enhancement factor [20]. The synthetic profiles were convolved with a Gaussian function representing the instrumental profile ($\lambda/\delta\lambda \approx 500000$). The calculated wavelengths are shifted to take into account the gravitational redshift. The 2D time-dependent surface intensity profiles are then spatially and temporally averaged before comparison with observations.

Figure 1 shows an example of a typical fit between synthetic and observed profiles. It is worthwhile to note that the remarkable agreement ($< 1\%$) is obtained without the use of the traditional tuned parameters, the so-called micro- and macro-turbulence. Indeed, the Doppler shifts due to the convective flows are naturally taken into account in the simulations. This is one of the major advantages of using the 3D hydrodynamical approach.

Concerning possible non-LTE corrections, they should be small for Fe i lines. Indeed, it was shown [21] that for the Sun the corrections between 3D LTE and 3D non-LTE models are smaller than 0.1 dex, which is better than the accuracy of laboratory measurements.

3. Results

The lines of interest for the RVS were selected by the Gaia Coordination Unit 6 of the Data Processing and Analysis Consortium (DPAC). For that work lines were considered sufficiently strong if observable in a typical G-dwarf star, like the Sun. In the present work, we consider 30 Fe i and Si i lines and the three strong Ca ii triplet lines. The chemical abundances were taken from [14] and are close to the meteoritic values: $\log\epsilon_{\text{Fe}} = 7.45$, $\log\epsilon_{\text{Si}} = 7.51$ and $\log\epsilon_{\text{Ca}} = 6.34^2$.

For each line, we compute a series of intensity profiles for several values of oscillator strengths,

\[ \epsilon_X = 10^{12} \frac{N(X)}{N(H)} \]
Figure 3. Fits of the synthetic (•) disk-center Ca\textsc{ii} triplet with the solar spectrum (——). The central depression is not well fitted since the line cores are formed in non-LTE conditions.

The results are shown in Fig. 2. The disagreement between the derived log $g_f$ from simulation and the log $g_f$ from the data base can be rather large for some lines (up to 0.8 dex). The situation is better when considering only lines having laboratory $g_f$-values [22]. For these 10 lines the agreement is better than 0.1 dex, which is very acceptable. The corrections for the lineshifts are of the order of 0.5 km s$^{-1}$.

We also consider the important case of the Ca\textsc{ii} triplet. As shown in Fig. 3, our 3D modelling leads to very good fits of the wings but is unable to fit the core (especially for $\lambda 854.8$ and $\lambda 866.2$). It is well known that non-LTE affects the central depressions of the Ca\textsc{ii} lines but weakly modifies equivalent widths (e.g. [23]), and therefore should not affect our log $g_f$ determination. Our proposed values of log $g_f$ are in agreement with recent calculations [24](labelled M07) to between 0.005 and 0.05 dex (see Table 1). The situation is slightly worse when we compare our data with those in VALD or NIST$^3$ ($\Delta$log $g_f \sim 0.1$ dex for $\lambda 849.802$).

| $\lambda$(nm) | 849.802 | 854.209 | 866.214 |
|---------------|---------|---------|---------|
| log $g_f$3D   | -1.309  | -0.410  | -0.683  |
| log $g_f$M07  | -1.356  | -0.405  | -0.668  |
| log $g_f$VALD | -1.416  | -0.463  | -0.723  |
| log $g_f$NIST | -1.318  | -0.360  | -0.622  |

It is important to emphasize that this work would have been impossible to accomplish using standard 1D hydrostatic atmospheric models, since the derived log $g_f$ would have been dependent on adjustable parameters. Concerning the lineshifts, the use of hydrodynamical simulations is the only possibility to take into account the contribution of the convective blue shift, which is essentially due to the bright granules (upflows).

$^3$ http://physics.nist.gov/PhysRefData/ASD/index.html
4. Conclusion
We have tested the \(gf\)-values extracted from the VALD data base for several metal lines found in the \textit{Gaia} spectral region. Our main conclusion is that the laboratory oscillator strengths agree well (< 0.1 dex) with values derived from 3D simulations, whereas other sources (semi-empirical values) are inaccurate, with a disagreement that can be as large as an order of magnitude (1 dex).

The astrophysical determination of \(gf\)-values, as done in this work, is so far the only possibility we have to correct atomic data for the \textit{Gaia}/RVS instrument. Either theoretical or laboratory measurements of \(gf\)-values would be more appropriate. We address this conclusion to laboratories to encourage new oscillator strength measurements in the infrared.

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