MODELLING SPECTRA OF FAST-ROTATING STARS: BEYOND SPHERICAL APPROXIMATION

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ABSTRACT

The Kurucz program suite is a standard tool for modelling photospheres and generating synthetic spectra. It has the advantages of being very well-tested, reliable, and useful for a wide range of stellar physical parameters ($T_{\rm eff}$, $\log g$, $[Z/Z_\odot]$). Here we improve on the original Kurucz assumption that even a fast-rotating star is considered to be of spherical shape, thus making possible to separately determine both components of the projected rotational velocity $v \sin i$; we also explore the advantages of porting the code to run it on an Intel-PC under Linux.

Key words: Stars: atmospheres; Stars: rotation.

1. ROTATION IN KURUCZ MODELS

The spectrum synthesis programs by R. Kurucz solve the equation of radiative transfer in a plane-parallel atmosphere (Kurucz 1970). Observed flux is calculated as a sum of contributions over a *spherical* surface, even for a fast-rotating star.

The Kurucz programs handle rotation (Kurucz & Avrett 1981) by:

1. calculating the spectrum of a non-rotating (i.e. $v\ \sin i = 0$) star, and
2. dividing the spherical stellar disc into discrete regions and applying to the stationary spectrum a Doppler shift proportional to the rotation velocity in each region.

This treatment of rotation leaves room for much improvement, as noted already by Kurucz himself: it is appropriate only for slowly rotating stars, because it does not take into account the deformation of the stellar disc induced by rotation. This point is illustrated in Figure 1, which shows the shapes of a star rigidly rotating at different fractions of the critical speed. Figure 2 plots different profiles of a spectral line which is assumed to be broadened only by rotation. The correct profile of a distorted star is compared to line shapes arising from spherical stars with the same angular velocity and with radii equal to the equatorial or polar radius of a distorted star. It can be seen that spherical geometry does not yield accurate profiles of spectral lines in stars when the rotation speed is a sizeable fraction of the critical speed. Another important conclusion from the figure is that, if using a code that only handles spherical stars, it is convenient to use the equatorial rather than the polar radius: the line profile will still be wrong but at least the maximum rotational speed $v \sin i$ will turn out right. However, accurate results can be obtained only by modelling stars with a rotationally distorted shape.

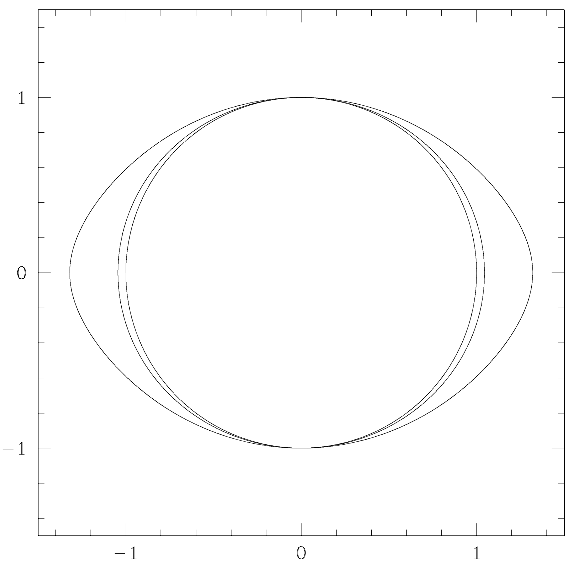

Figure 1. Shapes of rigidly rotating stars with equatorial velocities equal to 0%, 30%, and 80% of the critical equatorial rotation speed $v_o = (GM/r_{equator})^{0.5}$.

If the rotation is treated with a spherical approximation of the stellar shape, neither the rotation speed (v) nor the inclination angle of the rotation axis towards the line of sight (i) can be separately determined, because only their product $v \sin i$ can be measured. This is not the case any more if the star is modelled with an accurate rotationally distorted shape, because line profiles of stars rotating

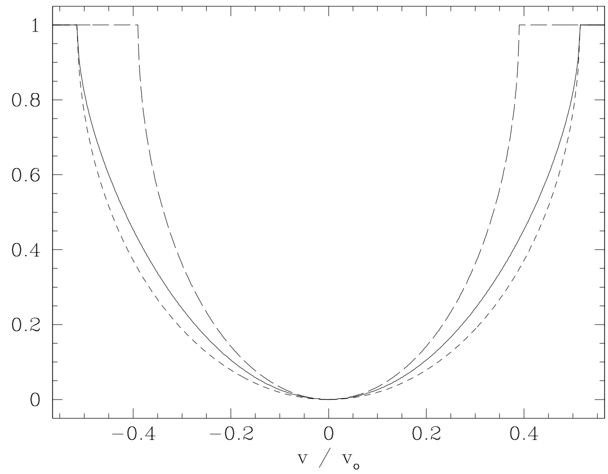

Figure 2. Rotational profiles for a star with a uniformly illuminated disc rotating at 80 % of the critical equatorial velocity (v_o) and seen at an inclination i =40° from the rotation axis. Three curves are plotted: a correct profile of the distorted star (solid), and profiles for two spheres rotating at the same angular velocity but with the radius equal to the polar (long dash) or equatorial (short dash) radius of the distorted star.

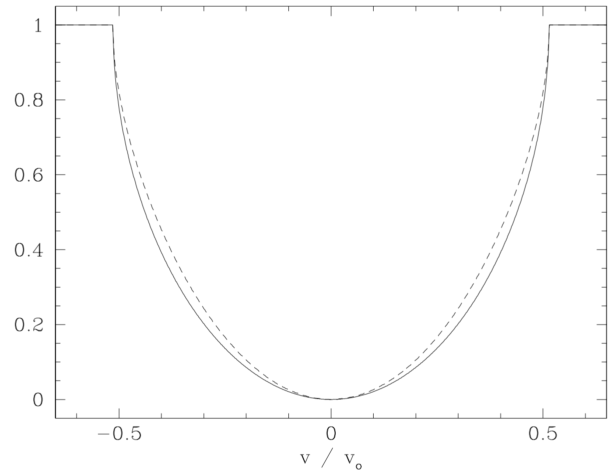

Figure 3. Rotationally broadened line profiles for two stars rotating with the same value of the product $v \sin i$ = 0.512v_o. The solid line corresponds to a star rotating at 51.2% of the critical speed and seen at i = 90°; the dashed line is for a star rotating at 80% of the critical speed, but seen at i = 40°.

with the same value of $v \sin i$ depend on the inclination angle i (Figure 3). Therefore, the values of v and i can be in principle determined separately. Note, however, that this is feasible only for fast rotators and for spectra with excellent signal to noise ratio.

2. RUNNING KURUCZ SOFTWARE WITH PC/LINUX

The code used to calculate Kurucz models and spectra must meet the following criteria:

1. **Efficiency**, to calculate a large grid of models in a reasonable time or to get custom models 'on the fly' (see below);
2. **Clarity**, so it is easy to modify and improve for more ambitious projects than initially devised by the authors;
3. **Portability**, so that the user is not tied to a particular platform he is not familiar with, or that might become obsolete in the future. Adherence to a programming language standard is crucial.

The Kurucz suite was created in the late 1960s. It is written in Fortran IV (a dialect of Fortran dating back from 1962) and works on VAX/Alpha machines running VMS. The code had to include numerous 'hacks' aimed at improving computation speed at the expense of readability and portability. Furthermore, the fact that Fortran IV conforms to no ANSI standard such as the ones followed by later versions of the language makes the behaviour of the programs completely compiler-dependent.

3. OUR PROJECT

Our project addresses both problems mentioned above. We aim for a better model of fast rotating stars by using rotationally distorted geometry; and we plan to carry out the work on PCs running Linux. In the future we hope to have a complete rewrite of the Kurucz suite in Fortran 95, along with full code documentation and an up-to-date user's guide.

This work uses ports of the Kurucz code from other authors:

1. A port in Fortran IV by Sbordone et al. (2004)
2. A port in Fortran 90 by John B. Lester, University of Toronto.

A comparison of spectra calculated under VMS and under Linux is shown in Figure 4.

As an example of the gain in efficiency when changing to a newer platform, Table 1 shows the execution times of the Kurucz programs under both Alpha-VMS and PC-Linux. In both cases, ATLAS generated a model of the physical state of the atmosphere with 72 layers in 135 iterations; SYNTHE used this model to generate a spectrum with a wavelength range of 50 Å at a resolution of 600 000. In the Linux platform, the spectrum was also degraded, both rotationally (for 5 values of $v \sin i$) and instrumentally (convoluted with a Gaussian profile for a final resolution of 20 000). The dramatic decrease in computation speed for the more modern Intel/Linux combination is obvious.

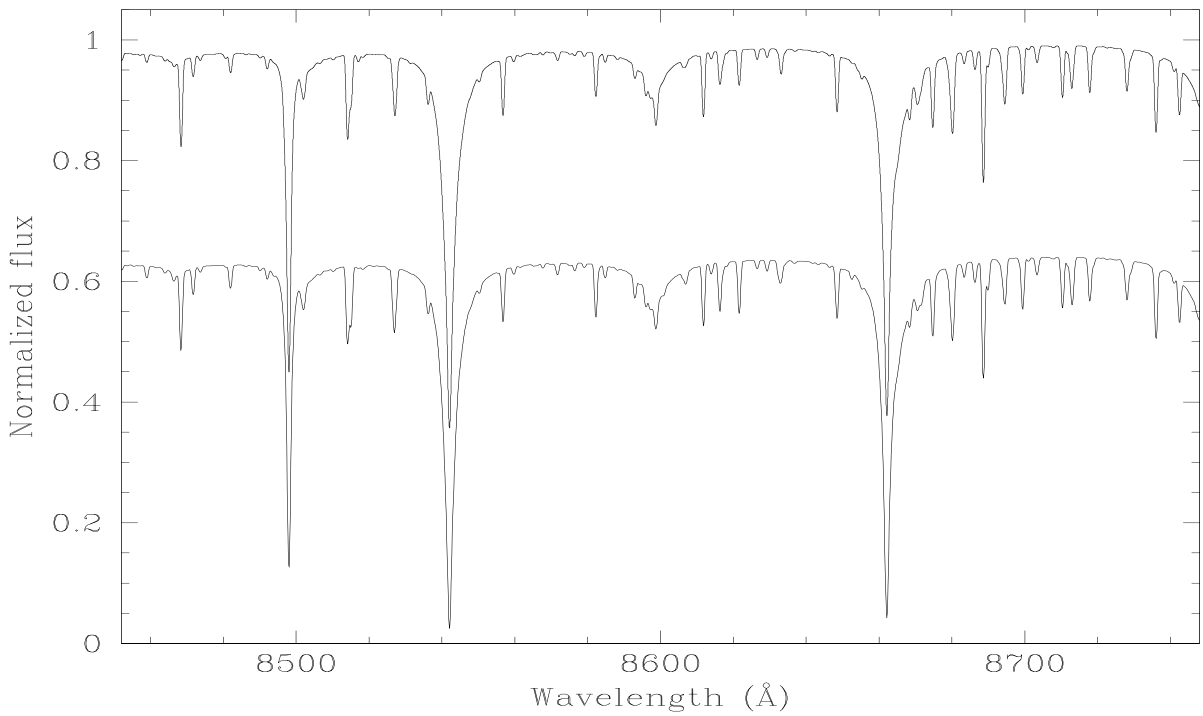

Figure 4. Synthetic spectrum of a star under both VMS (lower) and Linux (upper) in the Gaia wavelength range. The star has $T_{\rm eff} = 6500$ K, $\log g = 4.0$, $[Z/Z_{odot}] = 0.0$ and $v \sin i = 20$ km s^{-1}. The VMS spectrum is slightly offset downwards to improve the clarity of the figure. The coincidence of even the weakest lines can easily be appreciated.

Table 1. Comparison of execution times for the Kurucz software in Alpha/VMS and Intel/Linux. All times are in seconds. The figures for Alpha-VMS are from Sbordone et al. (2004).

	ATLAS	SYNTHE	Platform Info
VMS	478	69	AlphaServer 800, 500MHz, OpenVms
Linux	82	11	PIV 2.4 GHz Debian Linux

4. STELLAR ROTATION AND GAIA

At present there are approximately 20 000 stars with measured projected rotational velocities $v \sin i$ (Glebocki & Stawikowski 2000). Sorting them by stellar type and rotational velocity shows, as stated in Munari et al. (2001) and Soderblom (2001), that early-type stars (O, B, A, early F) show high values of $v \sin i$ (50 – 400 km s^{-1}), whereas late-type stars (late F, G, K, M) are slow rotators, with a $v \sin i$ generally lower than 50 km s^{-1}. This is generally attributed to the fact that late-type stars have convective envelopes, while early-type stars do not.

The Gaia Radial Velocity Spectrograph will make possible to study properties of stellar rotation in an unprecedented number of bright stars, estimated to be $\sim 2 \times 10^7$. Table 2 lists the accuracy of $v \sin i$ at the end of the mission as a function of magnitude for different stellar types: several slow rotators (such as K1 III, G5 MS/TO, F5 MS/TO) and a fast rotating B5 MS. An accuracy of approximately 5 km s^{-1} should be obtained at the end of the mission for late-type stars at $V \sim 15$. For B5 MS stars, an end-of-mission accuracy of $\leq$ 10–20 km s^{-1} should be obtained at up to $V \sim$ 10–11 (see Gomboc 2005). This huge amount of information will greatly improve our current knowledge on rotation and its influence on various fundamental aspects of stellar physics.

Table 2. Accuracy (in km s $^{-1}$) in the determination of the projected rotational velocity $v \sin i$ from spectra obtained by the Gaia spectrometer. The quoted numbers will be obtained at the end of the mission.

type of star	V magnitude	$v \sin i$ accuracy
K1 III [Fe/H]=0.0	15	4
K1 III [Fe/H]=-1.5	15	5
G5 V	15	6
F5 V ($v \sin i = 20$ km s^{-1})	15	15
F5 V ($v \sin i = 50$ km s^{-1})	15	20
B5 V ($v \sin i = 50$ km s^{-1})	12	25
B5 V ($v \sin i = 150$ km s^{-1})	12	40

5. SUMMARY

With this work we hope to develop a tool that accurately models early main-sequence stars (the most prominent fast rotators) and to detect any fast rotators among late-type stars. We hope to exploit the dependence of the line profile on the inclination angle of the stellar rotation axis to separately determine the two components of $v \sin i$ for these stars.

We also hope to provide a way to run Kurucz software as efficiently as possible, so that in the future the user can generate 'on the fly' a set of models and spectra tailored to his needs, instead of having to interpolate from a pre-calculated grid, like the ones already available in Munari et al. (2004) or Zwitter et al. (2004) .

ACKNOWLEDGMENTS

UJ acknowledges support from the Gaia RVS Consortium; TZ and AG acknowledge the support from the Slovenian Ministry for Education, Science and Sports; AG also acknowledges the receipt of the Marie Curie Fellowship from the European Commission.

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