Stellar Rotation from GAIA Spectra

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Abstract. Stellar rotation influences our understanding of stellar structure and evolution, binary systems, clusters etc. and therefore the benefits of a large and highly accurate database on stellar rotation, obtained by GAIA, will be manifold.

To study the prospects of GAIA measurement of projected rotational velocities \( v_{\text{rot}} \sin i \), we use synthetic stellar spectra to simulate the determination of \( v_{\text{rot}} \sin i \) at different resolutions (R=5000 - 20000) and S/N (10-300). Results on the accuracy of \( v_{\text{rot}} \sin i \), presented here, show that GAIA will be capable to measure also low rotational velocities (∼ 10 km/s), provided that the resolution is higher than 10,000, or preferably even higher.

1. Introduction

At present there are approximately 20,000 stars with measured \( v_{\text{rot}} \sin i \) (Glebocki, Gnacinski and Stawikowski 2000). Sorting them by stellar type and rotational velocity (Munari 2002, Soderblom 2001, Patten and Simon 1996):

- The effect of stellar rotation on stellar structure and evolution: rotation of a star influences its structure, luminosity, position on the HR diagram, life time etc. Rotation can via rotationally induced mixing lead to He and
N enrichment, chemically peculiar stars, it can cause turbulence, influence stellar winds and spots.

- The impact of differential rotation on stellar structure, surface phenomenology, models for generating magnetic fields etc.
- Stellar rotation as the indicator of age (for low mass ZAMS stars) through the magnetic breaking and the indicator of photospheric activity.
- In binary systems: stellar rotation is important in understanding the number of questions, such as the question of synchronization between rotational and orbital periods and the effectiveness of tidal energy dissipation.
- Rotational velocity as an indicator of angular momentum of solar type stars and how it is affected by the presence of massive distant planets.
- Stellar rotation as an indicator of age, total mass and binding energy in open clusters and as a clue to test various theories of fragmentation of the parent cloud.
- The orientation of rotational axis - are they really randomly oriented and therefore not connected with the rotation of the Galaxy, which is the question that only wide GAIA statistics can answer.

3. Simulating GAIA accuracy of $v_{\text{rot}} \sin i$

The important issue of GAIA contribution to stellar rotation physics is the accuracy of obtained $v_{\text{rot}} \sin i$. Here are presented results of simulating the determination of rotational velocities on synthetic stellar spectra. We used Kurucz synthetic stellar spectra database in the GAIA wavelength region.

To start the simulation we choose the spectrum with known $T$, $Z$, $\log g$, $v_{\text{rad}}$ and original $v_{\text{rot}} \sin i$, artificially add Poison distributed noise and afterwards fit it with noise-free spectra with various $v_{\text{rot}} \sin i$. As the best fitting spectrum we take the spectrum with minimum $\chi^2$ and repeat the test $N$ times. The accuracy is determined as the standard deviation error between the original and recovered $v_{\text{rot}} \sin i$:

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^{N} \left[ v_{i(\text{orig})} - v_{i(\text{rec})} \right]^2.$$

We used synthetic spectra of four star types: late G type giant ($T=4750$, $Z=-0.5$, $\log g=1.0$), K dwarf ($T=4750$, $Z=-0.5$, $\log g=4.5$), G type giant ($T=5500$, $Z=-0.5$, $\log g=2.0$) and early F type star ($T=7250$, $Z=0.0$, $\log g=4.5$), all with $v_{\text{rot}} \sin i=10$ km/s at different resolutions: $R=5000$, 8615, 17230 and 20000. Noise added corresponds to signal to noise ratio in the range of $S/N=10-300$ and the number of trials is $N=5000$.

As the fitting spectra we first use the spectra with stellar parameters ($T$, $Z$, $\log g$, $v_{\text{rad}}$) exactly the same as in the original spectrum, so that they differ only in $v_{\text{rot}} \sin i$. The obtained accuracy in such simulations is shown on Figure 1: as expected the accuracy is much better for high resolution and improves with
Figure 1. The simulated accuracy of $v_{\text{rot}} \sin i$ for four types of stars at resolutions $R=5743$, 8615, 17230, 20000 and as a function of S/N ratio. Other stellar parameters ($T$, $Z$, $\log g$, $v_{\text{rad}}$) are presumed to be exactly known, i.e. the same in the original and fitting spectra.

Figure 2. The same as Fig. 1. Dotted lines show the accuracy obtained if $\log g$ of fitting spectra is offset from its true value by 0.5.
better signal to noise. It should be stressed though, that this is the most ideal case, since other stellar parameters are precisely known.

Due to possible uncertainties in these, the accuracy of rotational velocity will generally become worse. To estimate the influence of those uncertainties on the accuracy of obtained rotational velocity, we performed the same simulations by fitting the original spectrum with spectral templates that had one of the parameters (T, Z, log g or $v_{rad}$) offset from its true value.

The least crucial factor turns out to be the uncertainty in log g. The dotted curves in Figure 2 show the accuracy of rotational velocity if fitted by spectra having log g offset for 0.5 from its original value.

More crucial is an accurate temperature. The error of 250 K in some cases keeps the rotational velocity error at 5-10 km/s, not improving with S/N, while the error of 125 K (Figure 3) is small enough that at least at high resolutions the accuracy is better than 1 km/s at high S/N.

One of crucial factors is an accurate metallicity. The error of 0.5 in metallicity leads to inaccurate rotational velocities (error >10 km/s), the smaller error of 0.25 is about a factor of 2 better and 0.1 is quite good for high resolutions (Figure 4). Note that the accuracy of the rotational velocity does not seem to suffer so much if the metallicity is underestimated than if it is overestimated by the same amount.

Crucial is also the accuracy of the obtained radial velocity. As shown in Figure 5, the error in radial velocity of 10 km/s leads to an error in rotational velocity of more than 10 km/s. If the radial velocity error is 5 km/s the error of rotation velocity is about 2 times smaller.
Figure 4. The same as Fig. 1. Dotted lines show the accuracy obtained if Z of fitting spectra is offset from its true value by 0.1.

Figure 5. The same as Fig. 1. Dashed and dotted lines show the accuracy obtained if $v_{\text{rad}}$ of fitting spectra is offset from its true value by (from top to bottom): 18, 9 and 6 km/s.
4. Conclusion

Table 1 gives the summary of stellar rotation accuracy obtained by simulations based on synthetic stellar spectra for different resolution and signal to noise ratio in the continuum. Columns 3-7 report the rotational velocity errors if the template used to recover the spectrum is ideal or mismatched for a given amount in temperature, metallicity, surface gravity or radial velocity.

Table 1. Estimated accuracy of $v_{\text{rot}} \sin i$ (in km/s):

| R    | S/N | ideal | $\Delta \log g=0.5$ | $\Delta T=125$ K | $\Delta Z=0.1$ | $\Delta v_{\text{rad}}=5$ km/s |
|------|-----|-------|---------------------|------------------|----------------|-------------------------------|
| 5000 | 10  | 10-20 | 10-20               | 10-20            | 10-20          |                               |
| 100  | 2-7 | 2-8   | 2-10                | 2-15             | 2-15           |                               |
| 10000| 10  | 7-12  | 7-12                | 7-12             | 8-13           |                               |
| 100  | 0.2-3 | 1-3  | 2-5                | 2-8             |               |                               |
| 20000| 10  | 1-4   | 1-4                | 2.5-4            | 1-4            | 5-10                          |
| 100  | <0.1| <0.1  | <0.1               | <0.1            | <0.1          | 5-10                          |

The results we obtained can be used only as a rough indicator of GAIA capabilities. We used synthetic stellar spectra without allowing for modeling uncertainties, chemical composition peculiarities etc. The results of simulations show that effects of combined errors in two of the template parameters (e.g. T and Z, or Z and log g) on the accuracy of rotational velocity are not always easily predictable. One should also be aware that the crowding of stellar spectra in GAIA focal plane may smear out some line profile details, which may be crucial in determining the rotational broadening of spectral lines. Nevertheless, we believe that measuring even small rotational velocities with GAIA is not out of reach, provided that the resolution is better than 10000, or preferably better than 15000.

References

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