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New "Pseudo-Rotating" Stellar Atmospheres

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Abstract

Regarding model atmospheres, rotation effects are mostly neglected, and, at best, the rotational broadening correction is being applied to a non-rotating synthetic spectrum. However, this approximation does not work for fast rotators ($v_{\mathrm{eq}} > 200\,\mathrm{km/s}$), where the effect of gravity darkening starts to be prominent. The need for this correction starts to be significant for stars hotter than F7. We introduce a new model atmosphere grid covering the region of the main-sequence A- and B-type stars. The model allows more robust follow-up studies, mainly to provide an alternative method to determine the inclination angle of the rotational axis by inversion. Calculating synthetic magnitudes and colors helps constrain the Main Sequence's rotational broadening and to determine other biases related to the stellar rotation that influence the parameters determined from CMD. Determining rotational parameters from gravity darkening provides an alternative way of disentangling $v \sin i$ values and leads to a more precise understanding of the distinct populations of rotating stars.

Model

The gravity-darkening law, in general form, is given by

$$F = \sigma T_{\mathrm{eff}} \sim C(\tilde{\omega}) g^{\beta},$$

where the exponent β can equal either 1 (von Zeipel law), 0.32 (convective envelope), or other value for the mixed case. Both constants were determined by Claret (1998, 2000, 2003). Integration of the surface gravity over Roche surface leads to the equation for the co-latitudinal gradient of effective temperature

$$T_{\mathrm{eff}}(\theta) = \frac{L}{4\pi\sigma R^2_{\mathrm{pole}}} t_n^4(\theta)$$

With given $T_{\mathrm{eff}}(\theta)$, $g(\theta)$ and a vector towards the line of sight Now, we can solve radiative transfer for each (θ, φ) point on the surface to get specific intensity $I_\nu(\mu)$. Consequently, we can integrate intensity over the surface to get total luminosity radiated in a line of sight

$$\mathcal{L}_{\succeq}(\tilde{\omega}, i) = \int_A I_\nu(\mu)|\mu| dA$$

The $L_\nu(\tilde{\omega}, i)$ is a synthetic spectrum of a rotating star, not yet corrected for rotational broadening.

To achieve more robust results, Espinosa Lara and Rieutord (2011) assume a generic function that gives the flux of the rotating star.

$$\mathbf{F} = -f(r, \theta)\mathbf{g}_{\mathrm{eff}},$$

where the effective gravity is very close to the Roche surface.

$$\mathbf{g}_{\mathrm{eff}} = \left(-\frac{GM}{r^2} + \Omega^2 r \sin^2\theta\right)\mathbf{e}_r + (\Omega^2 r \sin\theta\cos\theta)\mathbf{e}_\theta$$

The following substitution

$$\cos\vartheta + \ln\tan\frac{\vartheta}{2} = \frac{1}{3}\left(\frac{\Omega}{\Omega_k}\right)^2\left(\frac{r}{R_e}\right)^3\cos^3\theta + \cos\theta + \ln\tan\frac{\theta}{2}$$

leads to more refined gravity darkening model

$$T_{\mathrm{eff}} = \left(\frac{F}{\sigma}\right)^{1/4} = \left(\frac{L}{4\pi\sigma GM}\right)^{1/4}\sqrt{\frac{\tan\vartheta}{\tan\theta}}\, g_{\mathrm{eff}}^{1/4}$$

Synthetic Spectra and Synthetic Colors

To calculate the specific intensity of individual surface points, we use ATLAS12 code (Kurucz 2013) for A-type stars and cooler B-type stars, and TLUSTY code (Hubeny et al. 2021) for hotter B-type stars. Since the resulting spectra result from specific intensity integration, there is no need to do limb darkening correction. Nevertheless, the resulting spectra need to be corrected for rotational broadening. As explained by Pérez Hernández et al. (1999), rotational broadening does not change equivalent width, so passband convolution can be calculated before applying the rotational broadening correction.

Motivation

In comparison to non-rotating star, spectrum is altered not only in continuum, but also the shape of the spectral lines is modified as shown already by Maeder and Peytremann (1970). The luminosity of a fast rotator is slightly lower than that of the non-rotating counterpart; however, the mean effective temperature appears to be significantly lower. Fast rotators appear redshifted on an H-R diagram relative to slow rotators with the same composition and mass. At the same time, the apparent effective temperature strongly varies with the inclination of the rotation axis. A rotating star, oriented pole on, appears hotter than the same star oriented perpendicular to the line of sight.

Thanks to CHARA/MIRC, we can perform direct imaging of the rapid rotators. On the contrary to what was anticipated, the gravity-darkening exponent β appears to be significantly lower than 1 for A- and B-type stars (Monnier et al. 2014). This suggests that performing follow-up research via indirect methods on a larger sample is vital.

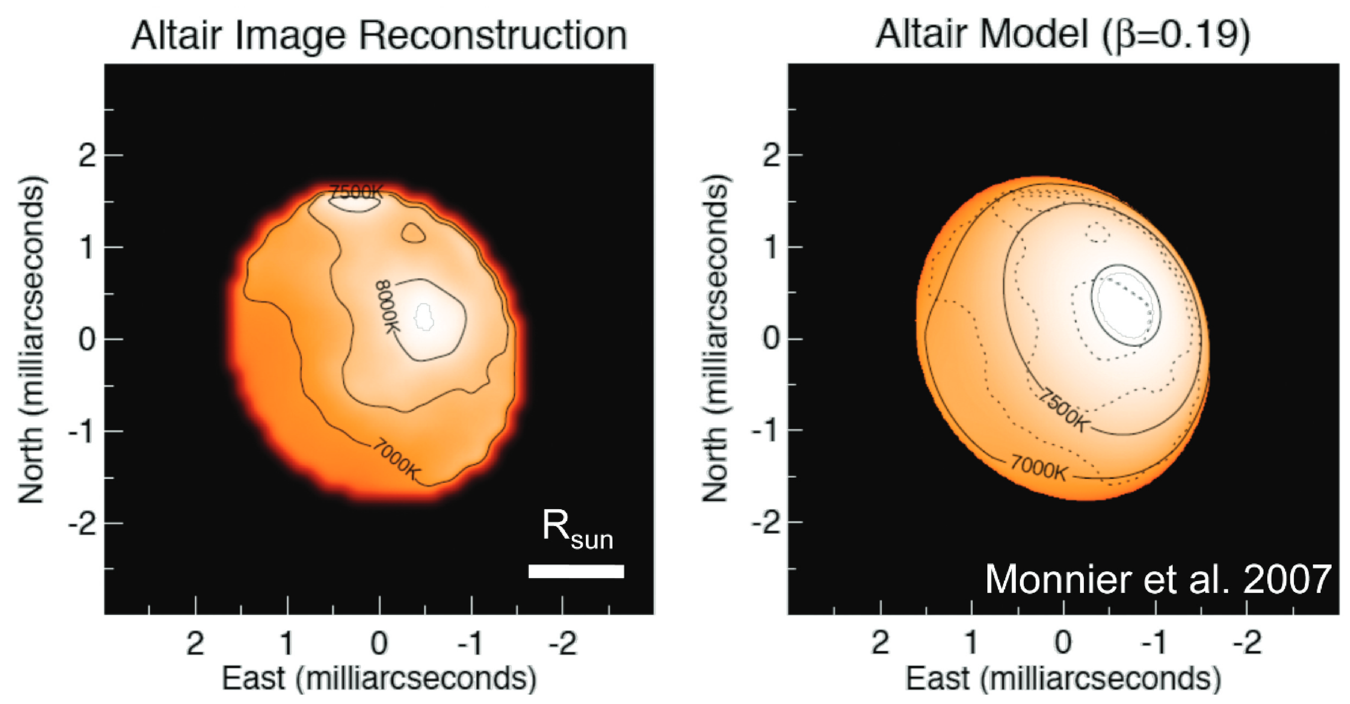

Fig. 1: First image of a MS star other than Sun compared to a model (Monnier et al. 2014).

The inclination of the rotational axis of individual stars is mostly unknown. The construction of a model atmosphere grid covering A- and B-type MS stars provides the possibility to perform an inversion to determine the previously unknown inclination of the rotation axis.

Since the position of rotating stars on an H-R diagram depends on rotational velocity and axial tilt, neglecting the population of the fast rotators in a star cluster could undermine the cluster age and distance determination given by isochrone fitting.

Challenges

The parameter space of the new model atmosphere grid consists of the following:

Parameter	Range	Step
effective temperature	$10\,000\,\mathrm{K} \le T_{\mathrm{eff}} \le 30\,000\,\mathrm{K}$	200 K
surface gravity	$1 \le \log g \le 5$	1 dex
metallicity	$+0.5 \le [M/H] \le -2$	0.5 dex
microturbulence	$0\,\mathrm{km/s} \le \xi \le 4\,\mathrm{km/s}$	1 km/s
equatorial velocity	$150\,\mathrm{km/s} \le v_{\mathrm{eq}} \le 250\,\mathrm{km/s}$	50 km/s
inclination	$5° \le i \le 90°$	5°, 10°

Tab. 1: Parameter space of the new model atmosphere grid.

This means we have 100 points in effective temperature, 20 points in surface gravity, 5 points in metallicity, 5 points in microturbulence, 6 points in equatorial velocity, and 10 points in inclination. In addition to that, each combination of parameters integrates over approx. 10^4 surface points. As a result, we need to perform 10^{10} model atmosphere calculations to complete the grid. In order to get at least close to this goal we needed to parallelize all computational tasks that are independent. At the same time, we managed to build up and maintain a dedicated computing cluster to fulfill this goal.

Conclusion

Construction of model atmospheres for A- and B-type stars incorporating gravity darkening with correction corrected by exponent (Claret 1998, 2000, 2003) can lead to slightly exaggerated gravity darkening gradient. Comparison with data suggests that the approach used by Espinosa Lara and Rieutord (2011) leads to more realistic results. We are actively working to reach full parameter space coverage which opens up new possibilities for the follow-up studies. Especially in the case of fast rotators, it can give us the more precise position of a star on an H-R diagram, leading to more accurate stellar parameters. The possibility of inverse calculation to determine the axial tilt of individual stars enables us to perform an extensive study of the inclination distribution in the Milky Way Galaxy and the Magellanic Clouds.

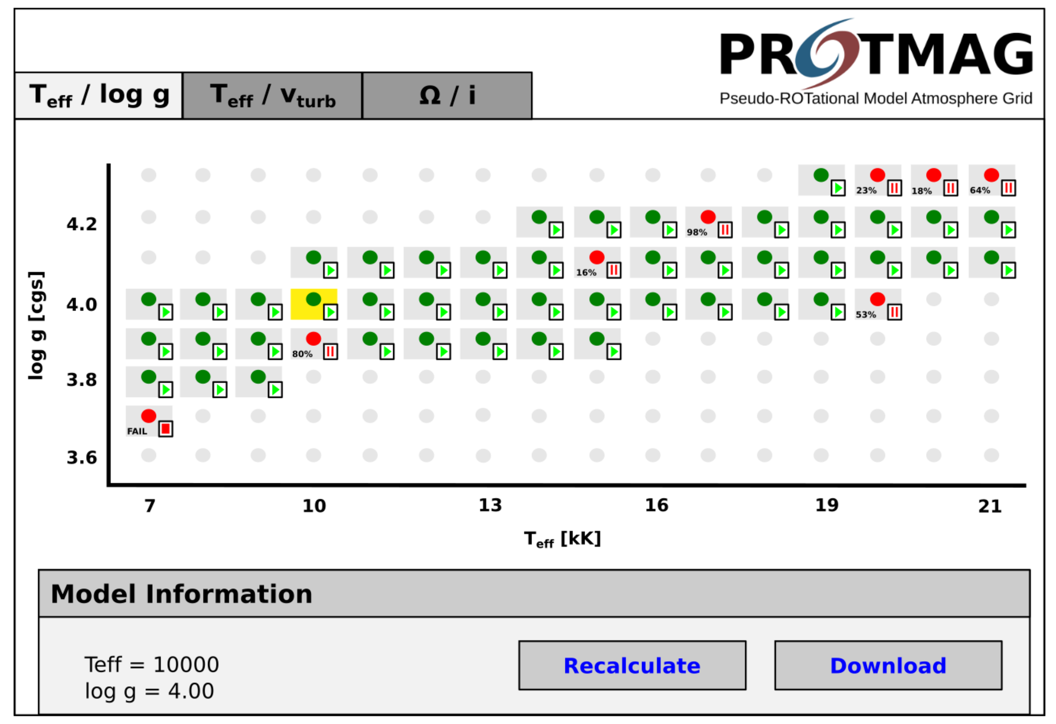

Fig. 2: Prototype of the Web user interface of the new model atmosphere grid.

Acknowledgements

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