NEW "PSEUDO-ROTATING" STELLAR ATMOSPHERES

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Abstract

When it comes to model atmospheres, rotation effects are mostly neglected, and, at best, the rotational broadening correction is 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 given by Von Zeipel's Theorem starts to be prominent. The need for this correction is significant for the main sequence stars hotter than F7. We currently work on a new model atmosphere grid for A- and B-type stars. The parameter space is extended for equatorial velocity and inclination to provide synthetic spectra and colors corrected for Von Zeipel's Theorem. Individual synthetic spectra are based on 1-dimensional plane-parallel results of the ATLAS12 code; thus, the new grid provides only a stationary "pseudo-rotating" model atmosphere. Despite this limitation, as we conclude in this contribution, the method used in our project still represents a significant improvement over the conventional approach.

Model

For simplicity, the model uses uniformly rotating barotropic or pseudo-barotropic approximation, where surfaces of effective potential, pressure, density and temperature coincide (presuming uniform composition) and follow axisymmetric Roche surface defined in spherical coordinates as:

$$x(\theta) = \frac{3}{\tilde{\omega}\sin\theta}\cos\left\{\frac{1}{3}[\pi + \arccos(\tilde{\omega}\sin\theta)]\right\}$$

(Harrington and Collins II 1968; Pérez Hernández et al. 1999), that depends only on dimensionless angular rotational velocity ($\tilde{\omega} = \omega/\omega_{\mathrm{crit}}$). This determines colatitudinal gradient of the effective potential that is also depends only on angular velocity for given mass and polar radius.

$$g(\theta) = \frac{GM}{R^2_{\mathrm{pole}}} g_{\mathrm{n}}(\theta)$$

This equation leads to gravity-darkening law, in general form 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 equation for the colatitudinal gradient of effective temperature

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

With given $T_{\mathrm{eff}}(\theta)$, $g(\theta)$ and a vector towards 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

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

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

Synthetic Spectra and Synthetic Colors

To calculate 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 are result of 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 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). Luminosity of a fast rotator is just slightly lower than the one of the non-rotating counterpart; however the mean effective temperature appears to be significantly lower. Fast rotators appears redshifted on an H-R diagram relatively to slow rotators with the same composition and mass. At the same time, apparent effective temperature strongly varies with inclination of rotation axis. A rotating star oriented pole on appears be 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 it is vital to perform follow-up research via indirect methods on larger sample.

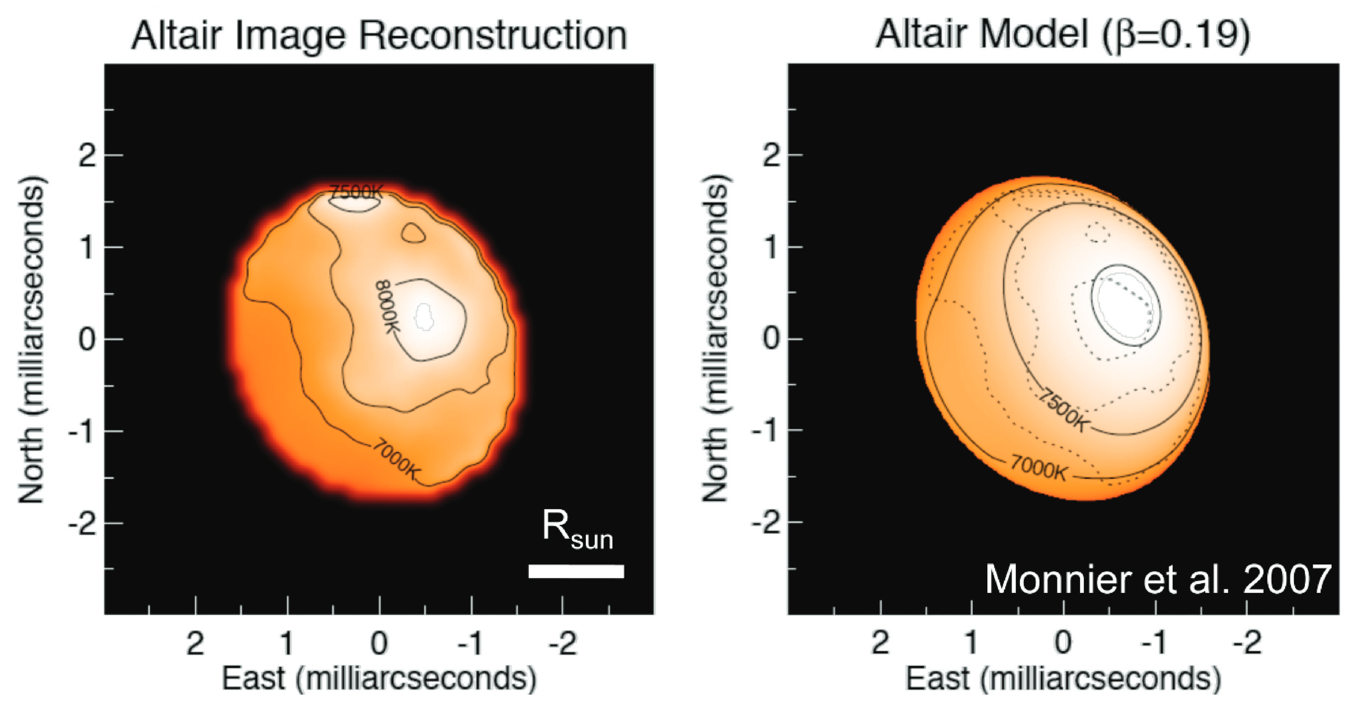

Fig. 1: First image of a MS star other than Sun compared to a model (Monnier et al. 2014).

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

Parameter space of the new model atmosphere grid consists of:

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

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

It means we have 100 points in effective temperature, 20 points in surface gravity, 5 points in metalicity, 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 dedicated a new computing cluster just to fulfil this goal.

Conclusion

Construction of model atmospheres for A- and B-type stars that incorporates gravitational-darkening with correction corrected by exponent (Claret 1998, 2000, 2003). This approach can be used in some extend for both radiative and convective envelope, as well as for the intermediate cases. Especially in case of fast rotators it can give us more precise position of a star on an H-R diagram, leading to more accurate stellar parameters. Possibility of inverse calculation to determine axial tilt of individual stars enable us to perform extensive study of the inclination distribution in the Milky Way Galaxy and the Magellanic Clouds.

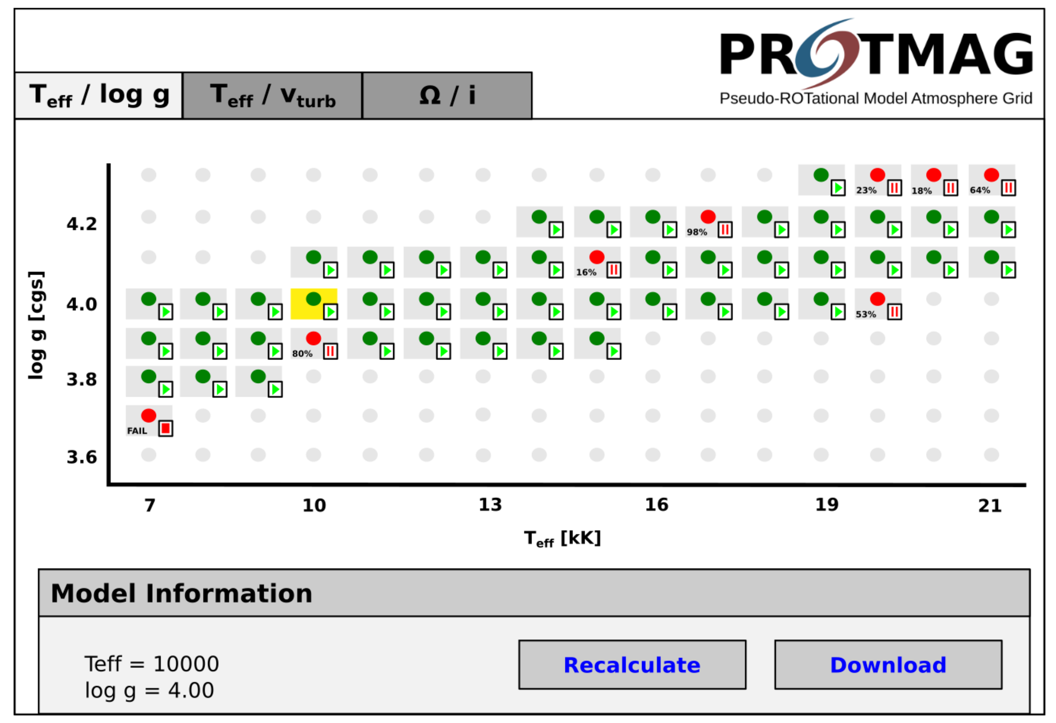

Fig. 2: An early prototype of the web user interface of the new model atmosphere grid.

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