Gravity and limb-darkening for space missions (CoRoT, Kepler, MOST, TESS) and plans for PLATO

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The example of TESS (Claret 2017, A&A)

the linear law

$$\frac{I(\mu)}{I(1)} = 1 - u(1-\mu), \tag{1}$$

the quadratic law

$$\frac{I(\mu)}{I(1)} = 1 - a(1-\mu) - b(1-\mu)^2, \tag{2}$$

the square root law

$$\frac{I(\mu)}{I(1)} = 1 - c(1-\mu) - d(1-\sqrt{\mu}), \tag{3}$$

the logarithmic law

$$\frac{I(\mu)}{I(1)} = 1 - e(1-\mu) - f\mu\ln(\mu), \tag{4}$$

and a four terms law introduced by us some time ago:

$$\frac{I(\mu)}{I(1)} = 1 - \sum_{k=1}^{4} a_k(1-\mu^{\frac{k}{2}}). \tag{5}$$

The numerical method for spherical models (r-method)

Based on the work by Wittkowskii et al. (2004)

Search for the maximum of the derivative of the specific Intensity as a function of $r = (1-\mu^2)^{1/2}$, instead of μ.

Adopted stellar atmosphere models (until now)

Atlas (plane-parallel, private communication)
PHOENIX (spherical, versions COND and DRIFT)

Ranges of effective temperatures, log g, metallicities and microturbulent velocities.

the ATLAS (plane-parallel geometry), PHOENIX-COND with spherical geometry (Husser et al. 2013), and PHOENIX-DRIFT also with spherical geometry (Witte et al. 2009). These grids cover together 19 metallicities ranging from 10^{-5} up to 10^{+1} solar abundance, $0 \leq \log g \leq 6.0$ and 1500 K $\leq T_{\rm eff} \leq$ 50000 K. The values of the microturbulent velocities (V_ξ) are 0, 1, 2, 4, 8 km/s.

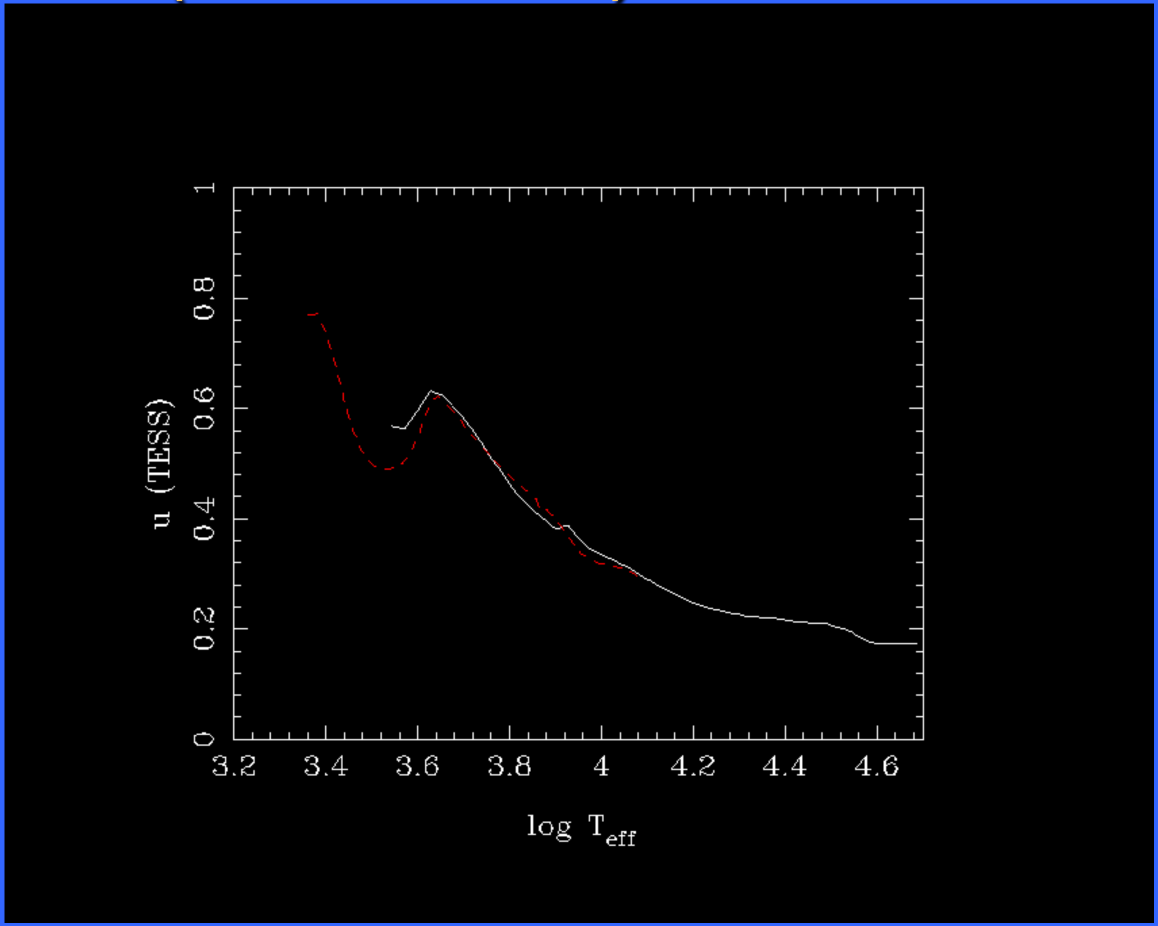
Results: limb-darkening

Often, the linear law is not a suitable approximation for limb-darkening.

However, it is useful to illustrate the comparison between models with different geometries and/or instruments with different photometric systems.

The linear coefficient *u* will be used in the next slides.

Comparison ATLAS x PHOENIX-COND (claret 2017)



(Claret 2017)

Fig. 2. Theoretical linear LDC for ATLAS models (continuous line) and PHOENIX-COND quasi-spherical ones (dashed line). Log $g = 4.5$, log[A/H]= 0.0, V_ξ = 2 km/s. TESS photometric system. LSM calculations.

Comparison TESS x Kepler

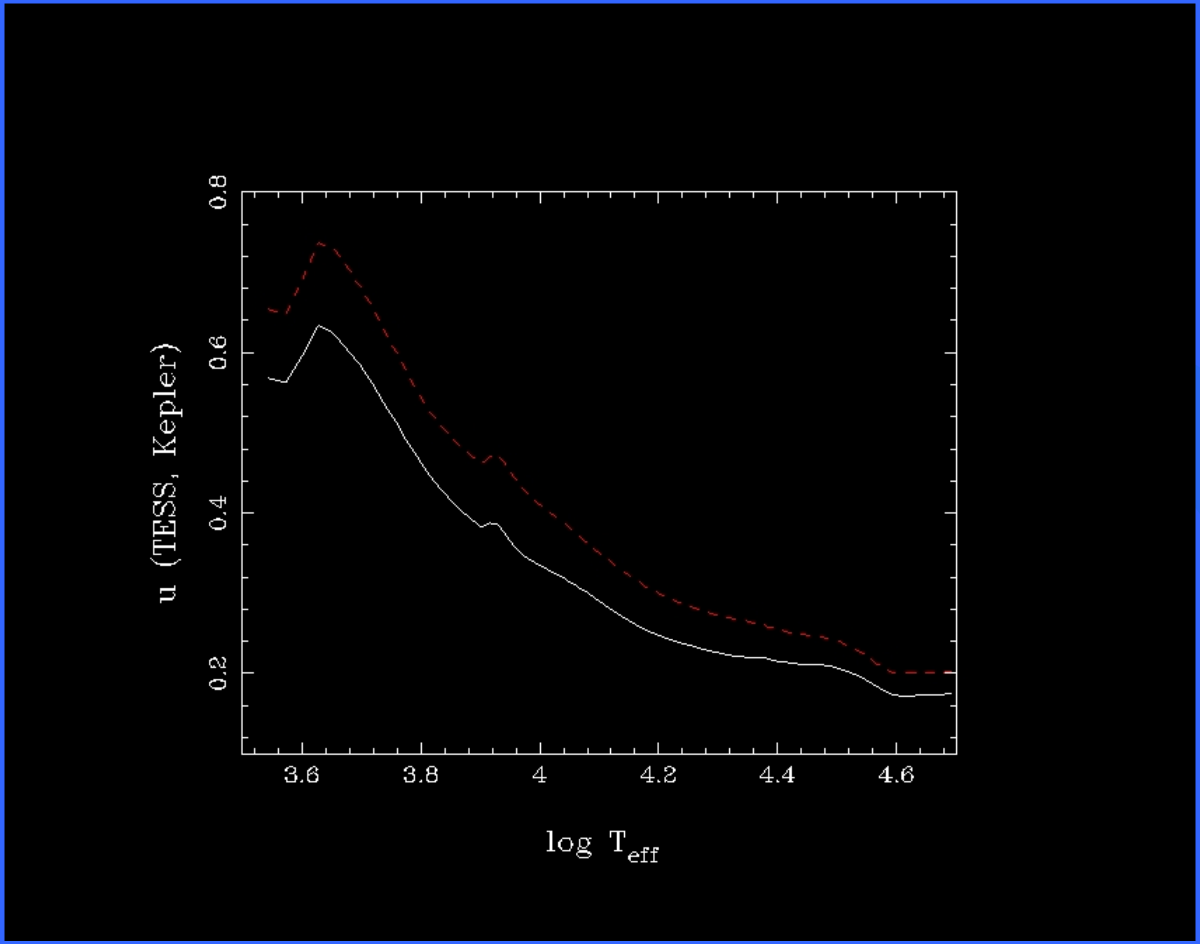


Fig. 4. Theoretical linear LDC for ATLAS models. Continuous line denotes TESS while dashed line represents the *Kepler* photometric system. Log g = 4.5, log[A/H]= 0.0, V_ξ = 2 km/s. LSM calculations.

Effects of metallicity and evolutionary status

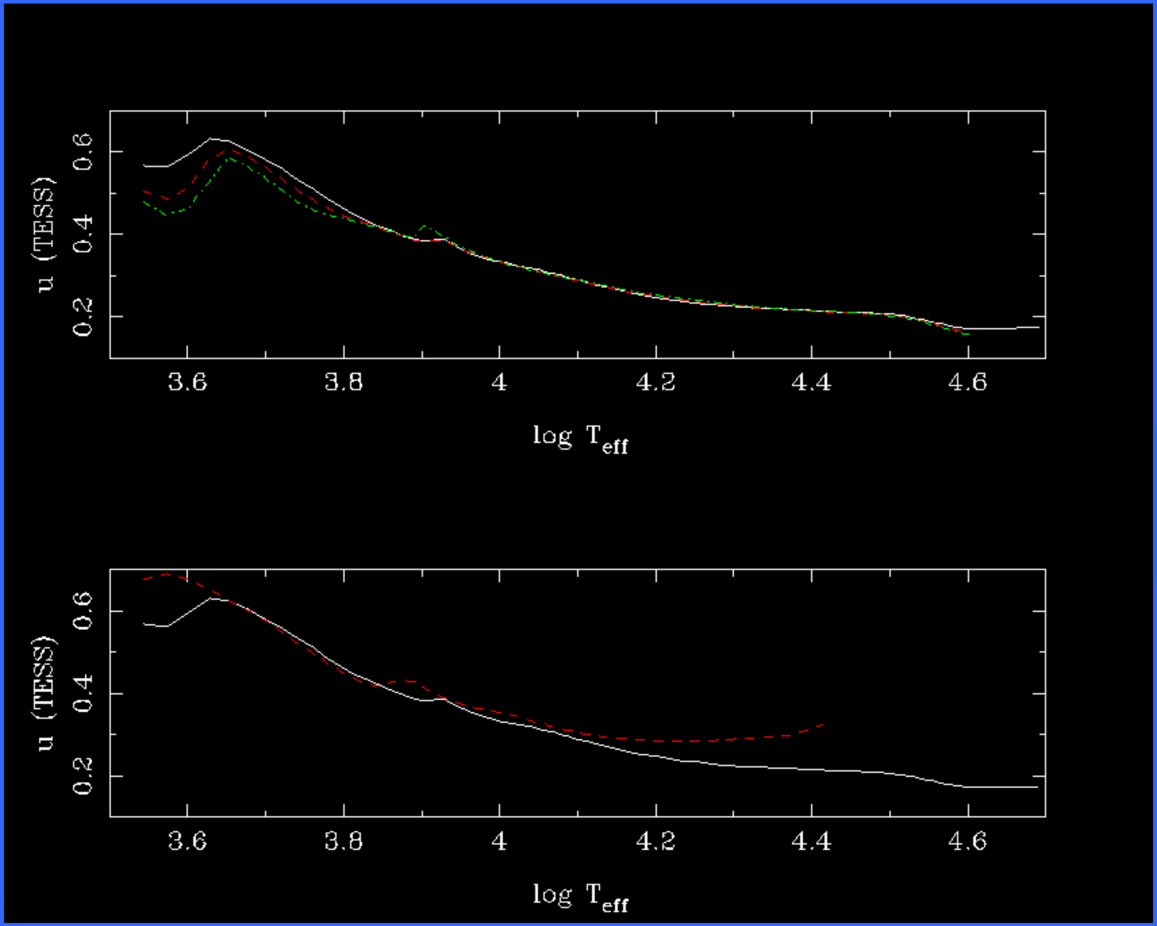
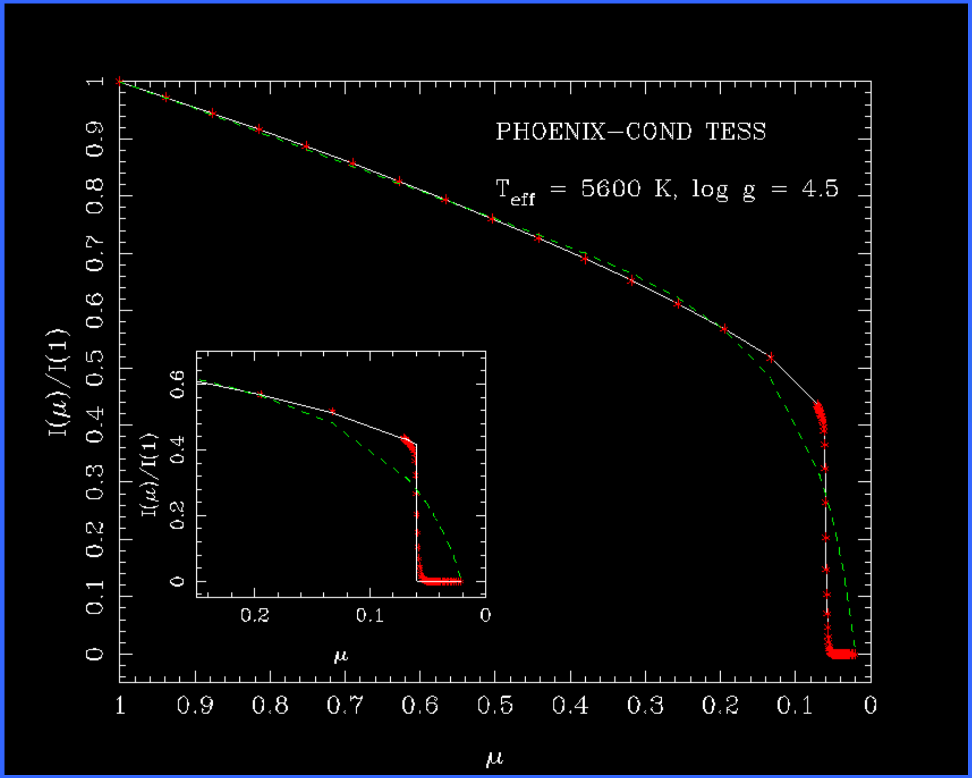


Fig. 5. Effects of metallicity and evolutionary status on the theoretical linear LDC for ATLAS models, TESS photometric system. Upper panel: continuous line denotes models with log[A/H]= 0.0 while dashed line indicates log[A/H]= -0.5 and dashed-dotted line those with log[A/H]= -1.0. Log g = 4.5 and V_ξ = 2 km/s for all models. Lower panel: continuous line denotes models with log g= 4.5 and dashed line represents models with log g= 3.0. Log [A/H] = 0.0 and V_ξ = 2 km/s for all models. LSM calculations for both panels.

A new method to compute limb-darkening coefficients atmosphere models with spherical symmetry

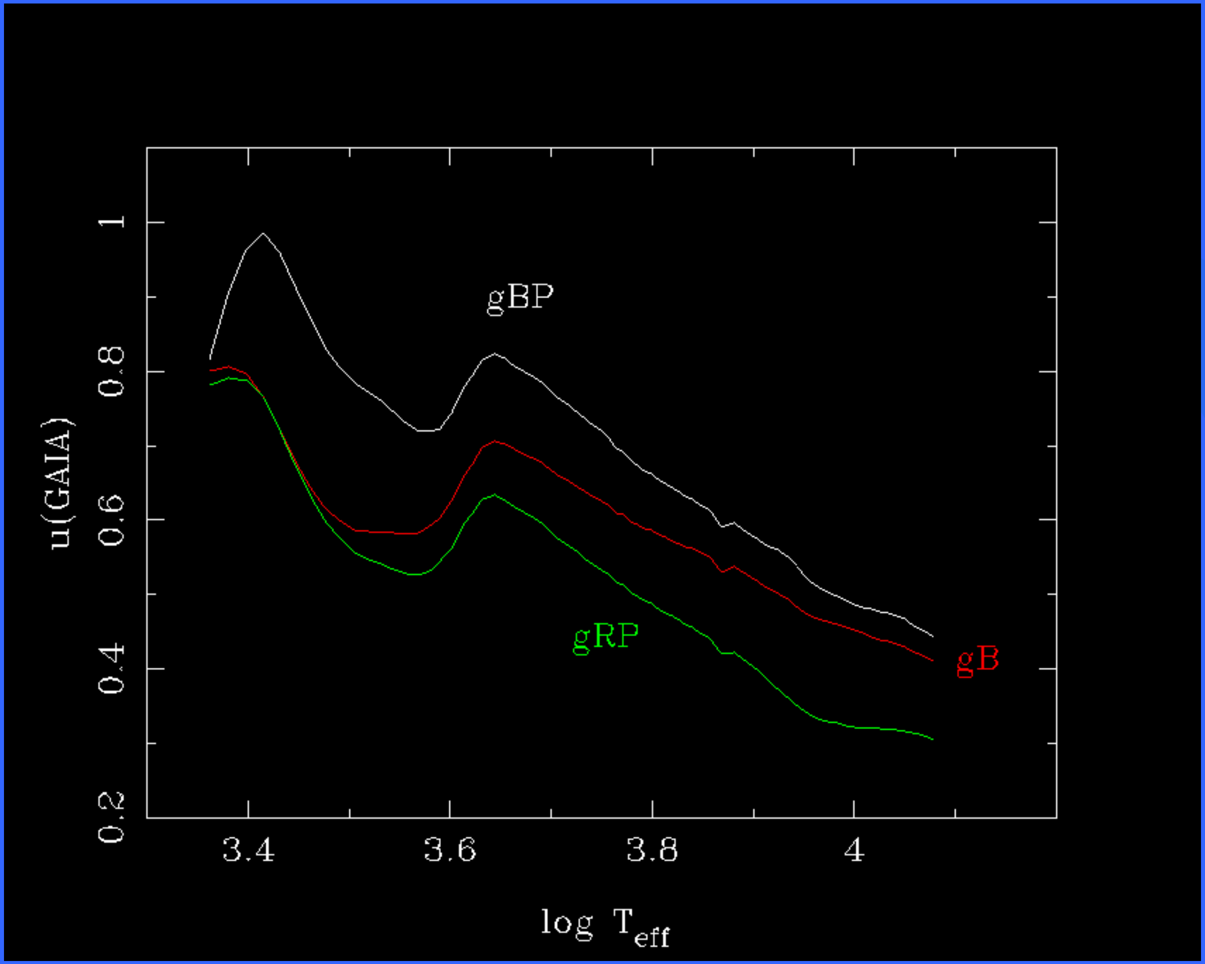


(Claret 2018)

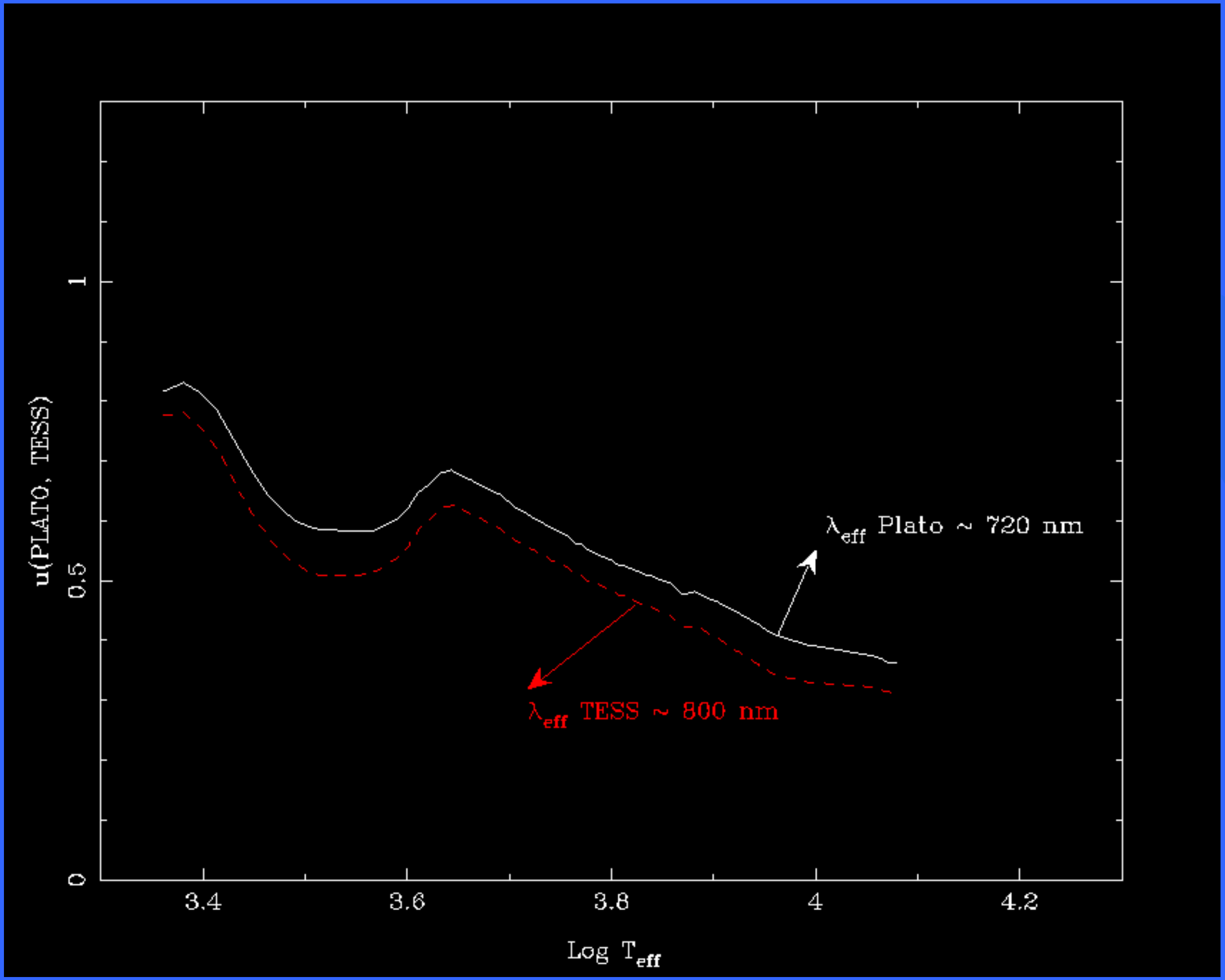
Instead of considering all the μ points in the adjustment, as is traditional, we consider only the points until the drop-off (μcri) of each model. From this point, we impose a condition I(μ)/I(1) = 0. Asterisks (red) represent the model intensities; dashed line (green) denotes the traditional fitting with 4 terms and continuous line (white) the new method with 4 terms. This new approach will allow the user to use directly the intensity distribution as they come from the stellar atmosphere models. For the quadratic law, as expected, the goodness of the fitting is a bit worse than that provided by the 4 terms, but it is still acceptable.

GAIA

(Claret 2019)



PLATO
First tests



Results: Gravity-Darkening Coefficients Distorted configurations

$$y(\lambda, T_{\rm eff}, \log[A/H], \log g, V_\xi) = \frac{1}{4}\left(\frac{\partial \ln I(\lambda)}{\partial \ln T_{\rm eff}}\right)_g .$$

Old formalism Martynov (1973)

$$y(\lambda, T_{\rm eff}, \log[A/H], \log g, V_\xi) = \left(\frac{d \ln T_{\rm eff}}{d \ln g}\right)\left(\frac{\partial \ln I(\lambda)}{\partial \ln T_{\rm eff}}\right)_g + \left(\frac{\partial \ln I(\lambda)}{\partial \ln g}\right)_{T_{\rm eff}} .$$

A new formalism by Claret & Bloemen 2011

1) New term; not negligible for cool giants

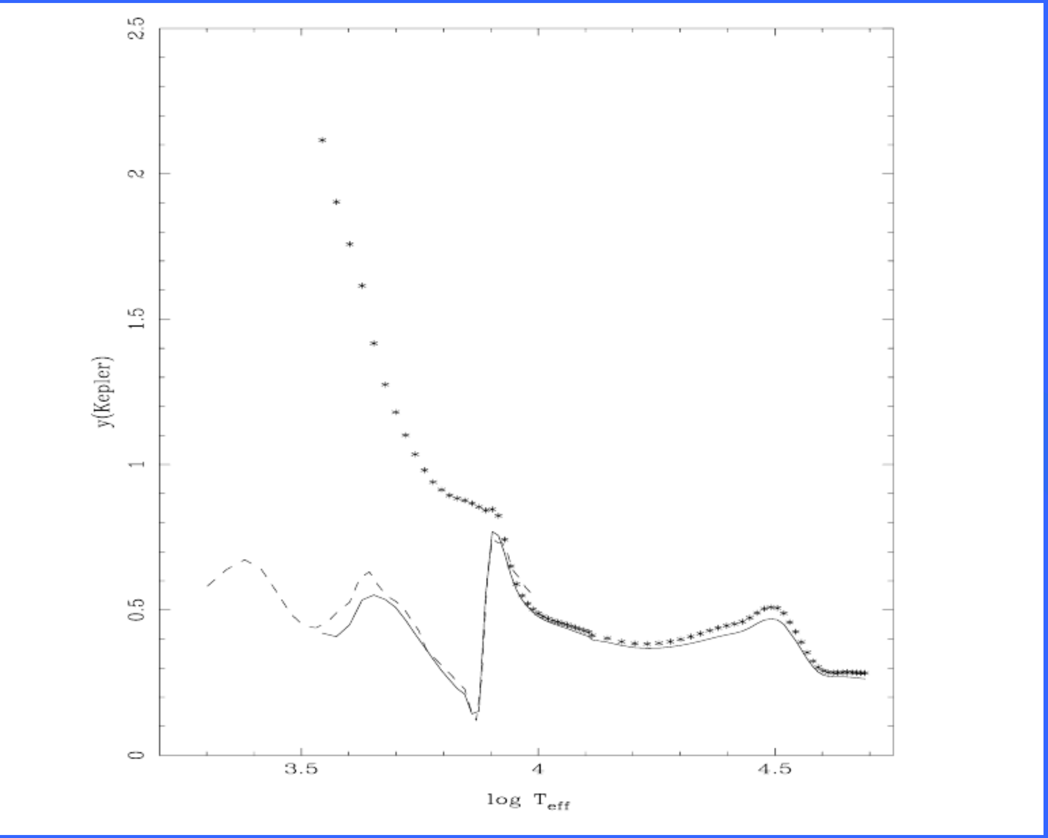
2) New term; effects of convection through the *gravity-darkening exponent* β_1

+

$$\boldsymbol{F} = \frac{4act^3}{3\kappa d}\left(\frac{dt}{d\Psi}\frac{\boldsymbol{g}}{\Lambda^4} + \frac{t}{\Lambda^6}\nabla\Lambda\right).$$

3) new equation for the deviations of the classical von Zeipel's theorem *(Claret 2012, 2015,2016)*

Gravity-Darkening



Theoretical gravity-darkening coefficientes for Kepler. The continuous line represents the ATLAS models (corrected), dashed one denotes the PHOENIX models (corrected) and asterisks represent the results using ATLAS (uncorrected).
[A/H] =0.00, Log g =4.5, V_{ξ} = 2.0 km/s.

Plans for PLATO (slide by T. Morel)

WP122: interfaces