Modeling Stellar Atmospheres with a Spherically Symmetric Version of the ATLAS Code: Testing the Code by Comparisons to Interferometric Observations and PHOENIX Models

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Abstract. One of the current opportunities for stellar atmospheric modeling is the interpretation of optical interferometric data of stars. Starting from the robust, open source ATLAS atmospheric code [1], we have developed a spherically symmetric code, SATLAS, as a new option for modeling stellar atmospheres of low gravity stars. The SATLAS code is tested against both interferometric observations of M giants by Wittkowski and collaborators, and spherically symmetric M giant NextGen models from the PHOENIX code. The SATLAS models predict interferometric visibilities that agree with the observed visibilities and with predicted visibilities, and the SATLAS atmospheric structures also agree with those from spherical PHOENIX models, with just small differences in temperature and pressure at large depths in the atmospheres.

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INTRODUCTION

Cool giant stars have low gravity, and are very luminous. They form a large fraction of the stellar population and it is important to understand these stars as a part of understanding stellar structure and evolution.

Optical interferometric observations are a powerful tool for understanding these stars and the ongoing development of interferometry is providing more precise details about the structure of stellar atmospheres. These observations also precisely measure limb-darkened angular diameters of stars and the center-to-limb variation of the intensity. This was done using K-band Very Large Telescope Interferometer (VLTI/VINCI) observations of \( \psi \) Phe, \( \gamma \) Sge, and \( \alpha \) Cet to test spherically symmetric PHOENIX stellar atmosphere models assuming local thermodynamic equilibrium (LTE) and plane parallel ATLAS models [2, 3, 4].

In this preliminary work we model the K-band VLTI/VINCI observations using a new version of the LTE stellar atmospheres code ATLAS that is spherically symmetric [5]. We also compare the structure of the models with effective temperature and gravities of these stars with PHOENIX models. The purpose of this analysis is to test how robust the SAAtlas code is at low gravity by comparing models to observations and to PHOENIX models, which is a benchmark for modeling stellar atmospheres.
TABLE 1. Input Parameters for the 3–D Grid of Model Stellar Atmospheres for Fitting Each Star.

| Star   | $L_{\text{Min}}(L_\odot)$ | $L_{\text{Max}}(L_\odot)$ | $\Delta L(L_\odot)$ | $M_{\text{Min}}(M_\odot)$ | $M_{\text{Max}}(M_\odot)$ |
|--------|---------------------------|---------------------------|--------------------|---------------------------|---------------------------|
| $\psi$ Phe | 630                      | 1580                      | 50                 | 0.6                       | 1.6                       |
| $\gamma$ Sge | 400                      | 700                      | 50                 | 1.0                       | 1.9                       |
| $\alpha$ Cet | 100                      | 2000                     | 50                 | 1.5                       | 3.0                       |

| Star   | $\Delta M(M_\odot)$ | $R_{\text{Min}}(R_\odot)$ | $R_{\text{Max}}(R_\odot)$ | $\Delta R(R_\odot)$ |
|--------|---------------------|---------------------------|---------------------------|--------------------|
| $\psi$ Phe | 0.2                | 60                        | 120                       | 20                |
| $\gamma$ Sge | 0.2                | 60                        | 120                       | 10                |
| $\alpha$ Cet | 0.1                | 60                        | 100                       | 10                |

FIGURE 1. Comparison of the predicted visibilities for three of the model stellar atmospheres with the observed data of $\psi$ Phe. (Right) with a close–up of the second lobe.

FITTING MODELS TO INTERFEROMETRIC DATA

We use the results of [2, 3, 4] to determine the range of luminosity, mass, and radius for each star, shown in Table 1, and calculate grids of spherically symmetric model stellar atmospheres.

To model the visibilities, we produce a grid of 480 models for $\psi$ Phe, 350 models for $\gamma$ Sge, and 1680 models for $\alpha$ Cet (there are more models for this case to test the fit over a much larger range). We find the best-fit limb-darkened angular diameter for each star using $\chi^2$ fitting and produce the Rossland angular diameter $\theta_{\text{Ross}}$, the layer with an Rossland optical depth of unity. The best-fit value for $\psi$ Phe is $\theta_{\text{Ross}} = 8.13 \pm 0.1$mas with $\chi^2 = 1.67$, for $\gamma$ Sge is $\theta_{\text{Ross}} = 6.02 \pm 0.01$mas with $\chi^2 = 0.64$, and for $\alpha$ Cet is $\theta_{\text{Ross}} = 12.1 \pm 0.05$mas with $\chi^2 = 0.98$. This is consistent with earlier results found using PHOENIX and plane-parallel ATLAS models. For the case of $\psi$ Phe, the $\chi^2$ value is smaller than that predicted using the PHOENIX code, though we predict the same value of $\theta_{\text{Ross}}$. The PHOENIX and SATLAS fits agree within the observational uncertainty. We also predict a smaller value of $\theta_{\text{Ross}}$ for $\alpha$ Cet, with a difference of 0.1mas. The differences may be related to the fact that we are using a larger number of models to fit the observations and to differences between PHOENIX and spherical ATLAS models. This may be an example of interferometric observations highlighting small differences
FIGURE 2. Comparison of the predicted visibilities for three of the model stellar atmospheres with the observed data of $\gamma$ Sge.

FIGURE 3. Comparison of the predicted visibilities for three of the model stellar atmospheres with the observed data of $\alpha$ Cet, (Right) with a close-up of the second lobe.

in computed intensity distributions between stellar atmosphere codes.

**COMPARISON WITH PHOENIX MODELS**

The comparison of the spherical ATLAS models to interferometric observations show that the new spherically symmetric version of the ATLAS code is a robust tool for studying stellar atmosphere; however it is important to compare this to similar PHOENIX models. Here we compare NextGen models \[^6\] with $T_{\text{eff}} = 3800, 3500 \text{ K}$ and $\log g (\text{cm/s}^2) = 0.5, 1$ and mass $M = 2.5$ and 5.0$M_{\odot}$.

By comparing the temperature structure as a function of the gas pressure, we can test if there exist differences in the properties of the computed stellar atmospheres that would also produce differences in the center-to-limb intensity structure. It is shown in Figure 4 that models produced by the SATLAS code are consistent with spherically symmetric, LTE PHOENIX models. There are only small differences between the temperature structure in this effective temperature and gravity range, most likely due to differences in the...
FIGURE 4. Comparison of the temperature structure of model stellar atmospheres computed by the spherical ATLAS code and PHOENIX NextGen models for two gravities log g = 0.5, 1.0. (Left) The models have an effective temperature of 3400 K and mass of $5\,M_\odot$. (Right) The models have an effective temperature of 3800 K and mass of $5\,M_\odot$.

codes. This comparison shows that the Spherical ATLAS code is robust and models low gravity stellar atmospheres in LTE as well as PHOENIX.

CONCLUSIONS

The goal of this work was to test new, updated version of the ATLAS code by comparing stellar atmosphere models with interferometric observations and comparing these results with results using the PHOENIX code. This work also directly compares the structures of cool, low gravity stellar atmosphere models computed using the spherical ATLAS code with NextGen PHOENIX models.

We find that the spherical ATLAS models fit the interferometric observations as well as PHOENIX models, and for case of $\psi$ Phe, the spherical ATLAS models fit a little better. By directly comparing our models to NextGen models, we see negligible differences in the temperature structure. It is shown that the spherical ATLAS code is a robust tool for stellar atmosphere studies. Please contact us if you would like a copy of the spherical ATLAS code.

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