Atmospheric model and synthetic spectrum of LL Aquarii using Kurucz model

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Abstract. Not only have interior structures, but stars also have an atmosphere. Physical processes and phenomena that occur in the atmosphere of a star also have a relationship with the stellar interior. One of them is the energy transport process produced from the stellar core and delivered to the surface and atmosphere of the star. The stellar atmospheric model is built by taking into account the changes in various parameters, such as mass depth ($\int \rho \, dx$), temperature ($T$), gas pressure ($P_{\text{gas}}$), electron density ($n_e$), Rosseland absorption coefficient ($\kappa_R$), and radiation pressure ($P_{\text{rad}}$) to the changes in optical depth ($\tau$) of the star. The stellar parameters used for building this model are from the LL Aquarii star which is a detached eclipsing binary star. The star system has a mass of 1.1949 $M_\odot$ for LL Aqr A and 1.0337 $M_\odot$ for LL Aqr B with effective temperatures of 6124 K and 5747 K respectively. The obtained atmospheric model is the result of bilinear interpolation of the Kurucz atmospheric grid model with $T_{\text{eff}}$ and $g$ parameters. The results of the LL Aqr atmospheric model become inputs for modeling the stars synthetic spectrum using the SPECTRUM program. Convolution with the rotational velocity of the star and spectral parameters of the spectrograph instrument used will produce a synthetic spectrum that corresponds to the spectrum acquired from observations. The results showed conformity with the observed spectrum with an O-C difference of 0.05 on average.

1. Introduction
   LL Aqr (HD 213896 or HIP 111454) is a detached eclipsing binary star system whose secondary components have characteristics similar to the Sun. The LL Aqr system has a spectrum class F9V for primary star and G3V for the secondary star, which means both are main-sequence stars. The LL Aqr system has an orbital period of 20.178321 days with a semimajor axis of 40.74 $R_\odot$ [1].

   The average magnitude of the LL Aqr system when not eclipse is $U = 9.850 \pm 0.062$, $B = 9.821 \pm 0.052$, and $V = 9.242 \pm 0.037$. This system are 137.8 ± 2.7 pc [2] away from Earth at RA = 22°34'42.2" (J2000) and Dec = -03°35'58" (J2000) [1]. The detached LL Aqr system (LL Aqr A and LL Aqr B) can be seen from the system configuration as shown in Figure 1. It can be seen that in the system, the components are still spherical without interaction between the stars.
Figure 1. LL Aqr system configuration with an inclination of 90° (up) and 0° (below) (orang circle indicates the size of the Sun).

The LL Aqr system had been previously analyzed by Ibanoglu, et al. [3] who first obtained the photometric solution and its UBV value. Then Griffin [4] obtained the system's orbital solution from the photoelectric radial velocity and Southworth [2] who analyzed the light curve and radial velocity of the system. Some of the main physical parameters of the LL Aqr system have been determined by various methods and are summarized in Table 1. In this paper, the atmospheric model of LL Aqr constructed using the known stellar parameter and then the synthetic spectrum constructed using those models.

| Parameter                  | Primary          | Secondary        | Reference   |
|----------------------------|------------------|------------------|-------------|
| Mass \([M_\odot]\)         | 1.1949 ± 0.0007  | 1.0337 ± 0.0007  | [1]         |
| Radius \([R_\odot]\)       | 1.321 ± 0.006    | 1.002 ± 0.005    | [1]         |
| Surface gravity (log \(g\)) [cgs] | 4.274 ± 0.004    | 4.451 ± 0.004    | [1]         |
| Effective temperature \([K]\) | 6124 ± 43        | 5747 ± 48        |             |
| Luminosity \([L_\odot]\)   | 2.20 ± 0.06      | 0.983 ± 0.033    |             |
| Metallicity ([M/H])        | 0.02 ± 0.04      | 0.03 ± 0.06      |             |
| Rotational velocity, \(v \sin i\) [km/s] | 3.5 ± 0.5        | 3.6 ± 0.4        | [1]         |

Weighted mean from [1] and [3].
Calculating from the radius of [1] and the effective temperature of the weighted mean [5] with [Fe/H] from [1].
2. Methods

2.1. Building the stellar atmospheric model

Modeling of the LL Aqr atmosphere was carried out using data grid from the Kurucz model [6] in the form of a metallicity, effective temperature, and log $g$ data grid. These atmospheres model were computed with the ATLAS9 model atmosphere program written by Kurucz [7]. For the components of the LL Aqr system, a [M/H] = 0.0 grid is used because this value is the closest to the metallicity value in the parameters previously obtained.

Table 2. Grid used for modeling the LL Aqr atmosphere.

| Effective temperature [K] | Log $g$ [cgs] | Effective temperature [K] | Log $g$ [cgs] |
|---------------------------|--------------|---------------------------|--------------|
| 6000                      | 4.0          | 5500                      | 4.0          |
| 6000                      | 4.5          | 5500                      | 4.5          |
| 6250                      | 4.0          | 5750                      | 4.0          |
| 6250                      | 4.5          | 5750                      | 4.5          |

For the components of the LL Aqr, the data grid ($T_{\text{eff}}$, log $g$) used are shown in Table 2. These are used to accommodate the effective temperature and surface gravity acceleration of LL Aqr A, which are $T_{\text{eff}} = 6124$ K and log $g = 4.274$ and $T_{\text{eff}} = 5747$ K and log $g = 4.451$ for LL Aqr B. The atmospheric model data grids consist of several parameters, namely mass depth ($\int \rho \, dx$), temperature ($T$), gas pressure ($P_{\text{gas}}$), electron density ($n_e$), Rosseland absorption coefficient ($\kappa_R$), radiation pressure ($P_{\text{rad}}$), and micro turbulent velocity ($\xi$). The Kurucz grid models include effective temperatures from 3500 K to 50000 K with 250 K difference between each grid. Whereas for gravitational acceleration is ranging from 0.0 to 5.0 with 0.5 difference between each grid.

To obtain the data set at the desired effective temperature and log $g$, an interpolation method from the grid boundaries of the Kurucz atmospheric model is carried out. The interpolation method used is the bilinear interpolation method with the following steps.

1. For the same effective temperature data for example 6000 K, with different log $g$ (4.0 and 4.5) an interpolation is performed to obtain data on the desired log $g$ ($T_{\text{eff}} = 6000$ K, log $g = 4.274$).
2. The same method was carried out at 6250 K effective temperature data with different log $g$ (4.0 and 4.5) and obtained data sets for $T_{\text{eff}} = 6250$ K and log $g = 4.274$.
3. From those processes, a data set for the desired log $g$ (log $g = 4.274$) is obtained with different effective temperatures (6000 K and 6250 K).
4. The two data sets are then interpolated to obtain the data set at log $g = 4.274$ and the desired effective temperature (6124 K).

2.2. Building the synthetic spectra

Atmospheric models that have been obtained are then processed using the SPECTRUM program [8]. SPECTRUM is a stellar spectrum synthetic program created by Richard O. Gray. SPECTRUM calculates the synthetic spectrum by input in the form of a stellar atmosphere model with local thermodynamic equilibrium (LTE) and a plan-parallel atmosphere assumption. The resulting synthetic spectrum is an intrinsic spectrum of stars that have not yet experienced broadening effects. In addition to the stellar atmosphere model input, other inputs are also needed as shown in Table 3. The wavelength range used is only a small part because the available observed spectra for the LL Aqr system (Figure 2) are in that range. This is done so that the obtained synthetic spectrum can be more easily compared to the observed spectra.
Table 3. Some inputs on the SPECTRUM program.

| Inputs                              | Value                     |
|-------------------------------------|---------------------------|
| Line list file                      | luke.lst                  |
| Micro turbulent velocity [km/s]     | 2.0                       |
| Wavelength range [Å]                | 5377.03 – 5390.23         |
| Wavelength step [Å]                 | 0.01                      |
| Rotational velocity ($v \sin i$) [km/s] | 3.5 (LL Aqr A)           |
|                                    | 3.6 (LL Aqr B)            |
| Limb-darkening coefficient          | 0.6                       |

Figure 2. Observed spectra for LL Aqr A (blue) and LL Aqr B (red) [1].

The intrinsic spectrum obtained is convoluted with the stellar rotational factor and the spectral parameters of the spectrograph instrument used. Convolution of the intrinsic spectrum model with a factor of the rotational velocity is carried out to see how it affects the line broadening that occurs in the spectrum because the greater the rotational velocity, the greater the line broadening effect occurs. This is done using the AVSINI auxiliary program on SPECTRUM. The input values needed for the AVSINI program include the rotational velocity and the limb-darkening coefficient.

The result of the convolution with rotational velocity factor then convoluted again with the spectral parameters of the spectrograph instrument used. For this reason, the SMOOTH2 auxiliary program is used as part of the SPECTRUM. This is needed to produce a synthetic spectrum model that is corresponding with the resolution of the instrument. HARPS (High Accuracy Radial velocity Planet Searcher) spectral instrument parameters are used for comparing the synthetic spectra with the observed spectra of LL Aqr stars. Some of them are shown in Table 4.

Table 4. Spectral parameters from the HARPS instrument

| Parameters     | Values          |
|----------------|-----------------|
| Spectral range [Å] | 3780 – 6910    |
| Resolution, R   | 120000          |
| $\Delta \lambda$ [Å] | 0.045          |
3. Results for Atmospheric Model

The results of the interpolation processes are shown in Figure 3 for the primary star, LL Aqr A, and Figure 4 for the secondary star, LL Aqr B. The first and second columns show changes in the six parameters (respectively from the top row: mass depth, temperature, gas pressure, electron density, Rosseland absorption coefficient, and radiation pressure) for the same temperature with different log $g$. While the third column shows the change in the profile of the six parameters for the same surface gravity (log $g$) with different temperatures. The interpolation results are indicated by the black line.

The profile of each parameter is plotted against the optical thickness value ($\tau$). This optical thickness is calculated using Eddington’s approximation from the radiative transfer equation,

$$T^4 = \frac{3}{4} T_{\text{eff}}^4 \left( \tau + \frac{2}{3} \right).$$

So, the value of $\tau$ can be calculated using temperature and effective temperature data in the stellar atmosphere model with the equation being

$$\tau = \frac{4}{3} \left( \frac{T}{T_{\text{eff}}} \right)^4 - \frac{2}{3}.$$

It appears that for $T = T_{\text{eff}}$, $\tau$ will have a value $\frac{2}{3}$. This is the definition of the boundary between the photosphere and the stellar atmosphere.
Figure 3. Interpolation results for LL Aqr A.
Figure 4. Interpolation results for LL Aqr B.

The atmospheric model of the six parameters for the two stars is shown in Figure 5. This model is the result of the last interpolation shown as a black line in the 3rd column of Figure 3 and Figure 4 with $T_{\text{eff}} = 6124$ K and $\log g = 4.274$ for LL Aqr A and $T_{\text{eff}} = 5747$ K and $\log g = 4.451$ for LL Aqr B. Both stars have almost similar graph trends. This is because the physical parameters of the two stars are also not much different. So, the profile that is expected to occur also will not be very different from each other.
4. Results for Synthetic Spectrum

The results of the synthetic intrinsic spectrum, the spectrum from observations, as well as the synthetic spectrum that has been convolved with the rotational velocity factor and instrument spectral parameters are shown in Figure 6. It also appears that the lines on the intrinsic synthetic spectrum are narrower and deeper. This is because the lines in the synthetic spectrum have not experienced the broadening effect of various factors. This is different from the convoluted spectrum, the lines appear wider and shallower because of the broadening effect due to stellar rotation and due to the limited resolution of the instrument.

The lower panel in both images shows an O-C diagram, which is the difference between the observed spectrum (observed) against the results of the synthetic spectrum that has been convoluted (calculated). The O-C value obtained is seen not too far from the value of 0 even though there are

Figure 5. Atmospheric models for LL Aqr A (blue line) and LL Aqr B (red lines).
several data points whose values reach 0.2. The results showed conformity with the observed spectrum with an O-C difference of 0.05 on average. This proves that the synthetic spectrum results obtained in general are not too much different from the spectrum of observations. Although it is clear that several lines appear to exist in the observed spectrum that is not well represented in the synthetic spectrum.

Figure 6. The results of the synthetic intrinsic spectrum (green), the observed spectrum (blue), the convoluted spectrum (red) for the LL Aqr A and LL Aqr B.

5. Conclusion
An atmospheric model of the LL Aqr system (A and B) has been obtained which is constructed from the Kurucz atmospheric data grid model. Interpolation of the data grid was carried out to obtain the atmospheric models whose parameters correspond to the physical parameters of each star. The obtained atmospheric model consists of the profile of mass depth, temperature, gas pressure, radiation pressure, electron density, and Rosseland coefficient to the optical depth of the star. There are not many differences between the LL Aqr A and LL Aqr B atmospheric model profiles due to the physical
parameters between them are almost the same. Those models are used as input to form the synthetic spectrum whose results are not much different from the observed spectrum.

6. Acknowledgment
This paper is based on a task given in the lecture AS 5103 Stellar Physics at Graduate School of Astronomy, FMIPA ITB. The research has been supervised by Hakim L. Malasan as the lecturer.

7. References
[1] Graczyk D, Smolec R, Pavlovski K, Southworth J, Pietrzynski G, Maxted P F L, Konorski P, Gieren W, Pilecki B, Taormina M, Suchomska K, Karczmarek P, Górska M and Wielgórski P 2016 A solar twin in the eclipsing binary LL Aqr A&A 594 A92
[2] Southworth J 2013 The solar-type eclipsing binary system LL Aquarii A&A 557 A119
[3] Ibanoglu C, Evren S, Tas G, Cakirli O, Bozkurt Z, Afsar M, Sipahi E, Dal H A, Ozdarcan O, Zengin Camurdan D, Camurdan M and Frasca A 2008 Spectroscopic and photometric observations of the selected Algol-type binaries – III. LL Aquarii, MP Delphini and NSV 20913 MNRAS 390 958–968
[4] Griffin R F 2013 Spectroscopic binary orbits from photoelectric radial velocities - Paper 230: Five Short-Period Double-Lined Binaries: HD 25788, HD 32704, HD 45191 (V455 Aur), and HD 213896 (LL Aqr) Observatory 133 156-184
[5] Asplund M, Grevesse N and Sauval J A 2004 The solar chemical composition Nucl. Phys. A 777 1-4
[6] Kurucz R L Kurucz/Grids of model atmospheres. Available from: http://kurucz.harvard.edu/grids.html Accessed on 22 August 2019
[7] Castelli F and Kurucz R L 2003 New grids of ATLAS9 model atmospheres Piskunov N, Weiss W W and Gray D F 210th Symposium of the International Astronomical Union Uppsala
[8] Gray R O and Corbally C J 1994 The calibration of MK spectral classes using spectral synthesis. 1: The effective temperature calibration of dwarf stars AJ 107 742-746