The Variability of the R Magnitude in Dynamical Models of AGB Stars

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March 2019

1 Abstract

This report will first give a brief background on asymptotic giant branch (AGB) stars and the characteristics that make them interesting to study. Some methods and tools used in the field are then introduced, before the photometric variability of these stars is investigated. This is achieved by using data from dynamical models of AGB stars with differing chemical abundances. The $R$, $J$ and $K$ bands of the $UBVRI$ system are specifically investigated to explore whether these are good candidates for AGB photometric and spectroscopic research. Lastly, the molecular features at these wavelengths are investigated to understand the impact that they have on the photometric variability during the pulsation cycle and which molecules are most prominent in this.

2 Origin and Characteristics

2.1 The Asymptotic Giant Branch

Lower mass stars of about $0.6M_{\odot}$-$10M_{\odot}$ are the progenitors of AGB stars. After core hydrogen and helium burning is no longer possible, low-mass stars evolve off of the Main Sequence to the red giant branch and increase in size and luminosity whilst decreasing in temperature. The asymptotic giant branch begins above the red giant branch and is almost parallel to it, hence the name. Stars of low to intermediate mass do not end their lives with a supernova explosion. Instead, the AGB phase ends with expulsion of the outer envelope which then develops into a planetary nebula once the ejected material is ionised. The exposed core is left as a white dwarf remnant and gradually decreases in temperature (Habing and Olofsson, 2004; Evans, 2002; Herwig, 2005). Figure 1 shows a typical evolutionary sequence for a star of $2M_{\odot}$ in a Hertzsprung-Russel diagram.

The AGB stage can be split into two parts: the early phase (E-AGB) and the thermally pulsing phase (TP-AGB). For E-AGB stars the He-burning shell is the largest energy source, but as this is depleted the H-burning shell becomes the main source (Herwig, 2005). During the TP-AGB phase nuclear reactions
Figure 1: Hertzsprung-Russell diagram of a complete $2M_\odot$ evolution track for solar metallicity from the main sequence to the white dwarf evolution phase. In the cooler section of the post-AGB phase, wiggles in the track are caused by numerical convergence difficulties. The blue track shows a born-again evolution (triggered by a very late thermal pulse) of the same mass, however, shifted by approximately $\Delta \log T_{\text{eff}} = 0.2$ and $\Delta \log L/L_\odot = -0.5$ for clarity. The red and green stars mark the position of the central stars of planetary nebulae. The number labels for each evolutionary phase indicates the logarithm of the approximate duration for a $2M_\odot$ case. Larger or smaller mass cases would have smaller or larger evolutionary timescales, respectively.

Herwig, F. 2005
in the stellar interior create instabilities which lead to recurrent thermal pulses. Whilst the core consists of carbon and oxygen, helium and hydrogen burning continue in shells further from the centre. When the He-burning shell is close to the H-burning shell, the resultant instability causes a helium shell flash and the luminosity briefly increases. As a result of the thermal pulses the carbon produced by helium burning is dredged up and alters the carbon/oxygen ratio on the surface of the star. These thermal pulses tend to reoccur on a scale of \( \sim 10^4 \) years (Habing and Olofsson, 2004). The TP-AGB phase is where the chemical enrichment of gas and dust to the interstellar medium occurs due to rapid mass loss. During the AGB phase mass loss rate is greater than the nuclear burning rate and the star runs out of fuel to burn, signalling the end of the AGB stage.

2.2 Characteristic properties of AGB stars

The luminosity of an AGB star is typically between 500 and 10000 \( L_\odot \), due to the giant radius, with a temperature between 2000 and 3500 Kelvin (Habing and Olofsson, 2004). A structure typical of a star in the AGB phase is shown in figure 2. As seen from this figure the centre of the structure consists of a small dense degenerate carbon-oxygen core, which is the basis for the final white dwarf, and where the majority of mass is found. This core is surrounded by a helium burning shell, a layer of helium, a hydrogen burning shell, a radiative layer and a convective envelope which is by far the largest contribution to the radius. Many evolved low to intermediate mass stars have extensive dust shells that absorb and re-emit radiation in the infrared, sometimes so opaque as to obscure the stellar radiation in the visible (Evans, 2002). It is this dust that is thought to facilitate the strong stellar winds normally seen in ABG stars, as radial pulsations alone are not strong enough to accelerate matter to the requisite escape velocity. Instead, radiation pressure on dust grains is the accepted driving mechanism for these winds (Habing and Olofsson, 2004).

2.3 Classification of AGB stars

As the atmospheric composition changes during the AGB phase, so do the spectra and these falls into three categories. The M-type stars have an atmosphere that is oxygen dominated. C-type stars, a class encompassing both R and N stars, are carbon dominated due to the dredge-up. In AGB stars carbon and oxygen mainly forms the stable CO-molecule and the element in excess will be free to form molecules and dust. As mentioned before, these grains play a large role in driving the stellar winds and mass loss, however the wind-driving dust species will vary depending on the composition of the star. In C-type stars, rather intuitively, the wind driver is thought to be photon absorption on amorphous carbon grain, whereas the more transparent M-type atmospheres the wind driver is photon scattering on \( \text{Mg}_2\text{SiO}_4 \) grains (Bladh et al., 2015).

Classification is also done via light curves, such as Mira Variables which have regular periods and large amplitudes at visible wavelengths. It is thought that these are the most evolved types. Semi-regular variables are split into type a,
which have small amplitudes but mostly regular periodicity and type b which have similar amplitudes but are less regular. Irregular variables are not periodic and have small amplitudes (Habing and Olofsson, 2004).

3 Research Tools

3.1 Photometric Bands and Colours

In order to study stars and other objects emitting radiation at various wavelengths, a range of passbands or filters that register flux in different sections of the electromagnetic spectrum are used. Although there are many different systems available, tailored to specific instruments or objects under observation, the standard is the \textit{UBV} system, standing for ultraviolet, blue and visible. The system used in this project is an extended version of this, with bands \textit{UX}, \textit{BX}, \textit{B}, \textit{V}, \textit{R}, \textit{I}, \textit{J}, \textit{H}, \textit{K} and \textit{L}. This continues the \textit{UBV} system well into the infrared end of the spectrum, which is important in the case of AGB stars as they emit at longer wavelengths than younger stars and have very dusty atmospheres, meaning radiation is absorbed and re-emitted in the infrared.

Taking the difference between the magnitudes in these passbands gives the colour index, for example the colour indices \( J - K \) and \( R - K \) that are used in this project. These indices are independent of distance and often used to demonstrate how blue or red the radiation emitted from the object is.

Figure 2: Schematic view of the structure of a 1M$_{\odot}$ star at the onset of the thermally pulsing AGB. Left: regions plotted against mass fraction; right: regions plotted against radius (from Lattanzio & Wood 2003).
magnitude system is inversely proportional to brightness so an object with a small $B - V$ magnitude is bluer than an object of larger colour index. In the $UBV$ system the filters are normalised to the star Vega. When two indices are plotted against each other the result is a colour-colour diagram (Carroll and Ostlie, 2014). Figure 4 shows an example of a colour-colour diagram. Three dynamical models are plotted on the same figure for $J - K$ and $R - K$.

### 3.2 Models of the atmospheres and winds

The structure and variability of AGB stars are studied by using dynamical models of the stellar atmospheres. These models give a picture of how the stellar atmosphere is structured and how this structure changes with time. The output produced by these dynamical models can then be compared with various observational data. The models in this project are based on the DARWIN code, which simulates atmospheric structure as a function of radial distance and time. The dynamical models are constructed from hydrostatic structures of the stellar atmospheres, set by the fundamental parameters (mass, luminosity and temperature) and chemical composition of the star. The variability of AGB stars is then simulated by varying the luminosity and radius at the inner boundary of the model. The dynamical model atmosphere is then constructed by solving partial differential equations (hydrodynamical, radiative transfer and grain growth) at each time increment to give snapshots of the radial structure of the atmosphere and winds. These can then be further analysed to produce spectral and photometric data (Bladh, 2014; Liljegren, 2018).

### 4 Implementation

<table>
<thead>
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<th>Model</th>
<th>$T_{\text{eff}}/K$</th>
<th>$L/L_\odot$</th>
<th>$M/M_\odot$</th>
<th>Period/days</th>
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<tbody>
<tr>
<td>C-type model</td>
<td>2800</td>
<td>7000</td>
<td>1.0</td>
<td>390</td>
</tr>
<tr>
<td>M-type model (nd15)</td>
<td>2800</td>
<td>7000</td>
<td>1.0</td>
<td>395</td>
</tr>
<tr>
<td>M-type model (nd315)</td>
<td>2800</td>
<td>7000</td>
<td>1.0</td>
<td>395</td>
</tr>
</tbody>
</table>

Table 1: Table of stellar parameters and periods used for the models. Note that nd15 and nd315 refer to a seed particle abundance, $n_{gr}/n_H$, of $1 \times 10^{-15}$ and $3 \times 10^{-15}$ respectively.

For this project, three different dynamical atmospheres were used: one carbon-rich and two oxygen-rich model AGB atmospheres. Table 1 shows various parameters used for the dynamical models. Note that temperature, luminosity and mass are the same, whereas the carbon-rich model has a shorter period. The difference between the two oxygen-rich models is the number of seed particles used for grain formation. The models consist of a series of snapshots containing data at a specific point in time as a function of radial distance. This includes density, gas temperature, gas pressure and optical depth as well
as chemical abundances. The data can then be used to calculated photometry and spectra in different bands in the \textit{UBVRI} system.

4.1 Motivation

It is the goal of this project to investigate the differences between the \(J\) and \(R\) bands of the models, using \(K\) as the difference in each colour magnitude. Previously, synthetic AGB atmospheres have been investigated in \(J-K\) against \(V-K\), for example in Bladh et al. (2013). The main difficulty with this is in measuring \(V\), \(J\) and \(K\) simultaneously with the same instrument and there is not a large quantity of data available with high phase coverage. To create colour-colour diagrams that properly demonstrate the photometric variability, observations covering the whole cycle is needed. Such phase-coverage might, however, be available in other photometric bands (such as the \(R\), \(J\) and \(K\) bands).

4.2 Methods

To create the relevant plots, a program was written using Python to extract information from the models. Firstly, the time increment labels were written to a numpy array. Next, the files containing the wavelength band magnitudes were read in and the \(R\), \(J\) and \(K\) values extracted for each time increment and added to an array. This was done for each of the models. The \(K\) magnitudes were then subtracted from the \(R\) and \(J\) magnitudes and the two differences plotted against each other in a colour-colour plot (see figure 3). The photometric data as a function of phase was then fitted to a sinusoidal curve in order to create smooth loops, as seen in figure 4.

It is useful to have an example of the spectral energy distribution (SED) to look at how the SED varies in the chosen filters. To this end a file was chosen at minimum phase and the SED plotted over all wavelengths on a logarithmic scale. The pass bands used in the colour-colour plot were then highlighted in the figure to indicate the wavelength regions they cover as shown in figure 5. The light curves of \(R\), \(J\) and \(K\) were also plotted as a function of phase in figure 6 to demonstrate that \(R\) and \(J\) are approximately sinusoidal, whereas the \(K\) band varies less.

4.3 Investigating contributions from molecules and dust

To further explore the aspects involved in the photometric variability of the synthetic stellar atmospheres, the models were calculated without including the dust opacity. The comparisons are shown in figure 7. Another important factor and difference affecting the magnitudes during the pulsation cycle is the varying molecular abundances. To demonstrate this, the most significant molecular contributions were plotted in the wavelength region from 0.2-2.4 microns which covers the \(R\), \(J\) and \(K\) bands. Only one of the oxygen-rich models was used (with higher number density of seed particles). The molecular information was
Figure 3: Unfitted colour loops for the three different models used in the colours $J - K$ and $R - K$. These were then fitted to a sinusoidal curve, as shown in figure 4. Here $nd15$ and $nd315$ have the same meaning as in table 1.

Figure 4: The colour loops from figure 3 after being fitted to a sinusoidal curve. It is noticeable that the two M-type models show similar variability while there is a marked difference in the C-type model.
Figure 5: Spectral energy distribution of a minimum phase for the C-type AGB star model. The passbands of interest, $R$, $J$ and $K$, are highlighted.

Figure 6: Photometric variations of the carbon-rich model in the $R$, $J$ and $K$ filters.
Figure 7: Fitted colour loops for the C-type model and one M-type model (nd315) atmosphere, calculated with and without dust.

gained by performing spectral calculations for one molecular species at a time (turning off contributions from atomic lines and dust). The spectral contribution from each molecule was plotted separately in the considered wavelength region and discarded if the visibility did not reach 0.1. The remaining molecules with significant features were then compared in figures 8 and 9.

5 Discussion

The colour-colour diagram for the models, shown in figure 4, demonstrates a small variation in $J-K$ and a large variation in $R-K$ for both M-type models. The oxygen-rich model with more seed particles has a more elongated loop, reaching to larger colour indices on both axes. The C-type model, however, shows greater variation in $J-K$ suggesting that its atmosphere is more heavily influenced by dust. This correlates with the results from Bladh (2014) where the M-type models were also found to have larger variation in $V-K$, most probably due to changes in the molecular abundance and transparency of the grains involved.

As mentioned, amorphous carbon is considered the main wind driver in C-type AGB stars whereas Mg$_2$SiO$_4$ is thought to be the main driver in M-type stars. The differences between these two materials also affect the emission strength in differing bands. Magnesium-rich silicates are transparent (Bladh et al., 2013), whereas carbon dust is much more opaque and will redistribute the stellar light from the visual to the infrared wavelength region. Inspection
Figure 8: Important molecular contributions in the spectrum for the C-type model in wavelengths spanning the $R$ band to $K$ band - 589 nm to 2385 nm.

Figure 9: Important molecular contributions in the spectrum for the M-type model in wavelengths spanning $R$ to $K$. 

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of figure 7 shows that the dust-free C-type model emits more strongly in $J$ and $R$, though particularly in $J$. There is also a larger variation in $J - K$, supporting the assertion that carbon-rich atmospheres and their variability tend to be dominated by dust, dwarfing the effect of the changing molecular abundances. The colours of the oxygen-rich model, however, barely change when the dust opacity is omitted and so it seems evident that the variability here is dependent on changes in the molecular abundance.

Figures 8 and 9 offer more insight into the molecular contributions to the SED and differences between the two types. In AGB stars, carbon and oxygen will create the stable CO-molecules, leaving the excess element of these two to form other molecule species. The plot for the M-type model is dominated by different oxides; TiO, VO and ZrO show prominent molecular features in the $R$ band and probably account for the large variation in $R - K$. These molecular features decrease quite significantly at longer wavelengths. The strong molecular features in the $R$ band region probably accounts for the larger $R - K$ variation.

As mentioned previously, carbon-rich atmospheres are dominated by the carbon dust. However, the dust-free model still shows variation in colour due to molecular changes. It can be seen that for the molecules in the C-type model there is a large variation in CN in the $R$ band which is overtaken by $C_2$ heading towards longer wavelengths. $C_2H_2$, $C_3$ and CO only become significant at wavelengths greater than about 1.2 $\mu$m, which may account for the C-type’s greater variability in $J - K$ rather than $R - K$. These molecules are all carbonaceous due to the excess carbon abundance.

6 Conclusion

Figure 7 shows that the $R - K$ and $J - K$ colours are dominated by dust for C-type AGB stars, whereas M-type AGB stars are not strongly affected. Figures 8 and 9 offer more insight into how molecular features in the atmospheres change over a pulsation cycle. This is particularly relevant for M-type atmospheres due to the transparency of their wind-driving dust species. These results correlate with results from previous papers such as Bladh (2014) where the colour-colour plots for C-type and M-type models were clearly separate, with the dust-dominated C-type model showing more variation in $J - K$ and the largely unaffacted M-type more variation in $R - K$. Radiation pressure on dust drives the winds of AGB stars (Höfner and Olofsson, 2018) so investigation into the properties of wind-driving dust species is crucial to understand AGB mass-loss processes. However dynamical models must be matched to observations to check reliability and robust data is needed for the comparison.

In light of the information able to be gleaned from the figures in this report, it seems that investigations in the $R$, $J$ and $K$ bands could well be a viable alternative to $V$, $J$ and $K$ observations. As mentioned before, data in these bands can be measured simultaneously with one instrument and there exist more studies with adequate phase coverage. Apart from the fact that AGB stars are more complex and dynamic than many other stars, further investigation is also
important for other fields, such as the chemical evolution of galaxies and the cosmic matter cycle.
References


