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Solving the M-Dwarf Luminosity Problem

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Abstract

For low-mass, pre-MS, M-dwarf stars with effective temperatures (T_{eff}) ≲ 4000 K, the stellar models systematically over-predict flux by about a factor of 2 in g-band photometry. Incorrect model fluxes for pre-MS stars can lead to incorrect stellar ages and hence (for example) incorrect planet formation timescales. Here we show that the difference in flux between the models and the data can be explained by a radius inflation of about 10%. We show that the resulting inferred temperatures match both the SEDs and the optical spectra.

1. Introduction

It is shown in Stauffer et al. (2007) and Bell et al. (2012) that for stars in the Pleiades with a T_{eff} ≲ 4000 K, models systematically overestimate the flux by a factor of 2 at 0.5 μm. This discrepancy decreases with increasing wavelength, disappearing at 2.2 μm. **Figure 1** shows the comparison between model isochrones and the observed clusters. To investigate this problem we use the BT-Settl CIFIST (Allard 2011) stellar model atmospheres to generate a grid of synthetic photometry. We utilise this grid to fit synthetic photometry to visible, near-IR and mid-IR broadband photometry, which determines the best fitting temperature (T_{SED}).

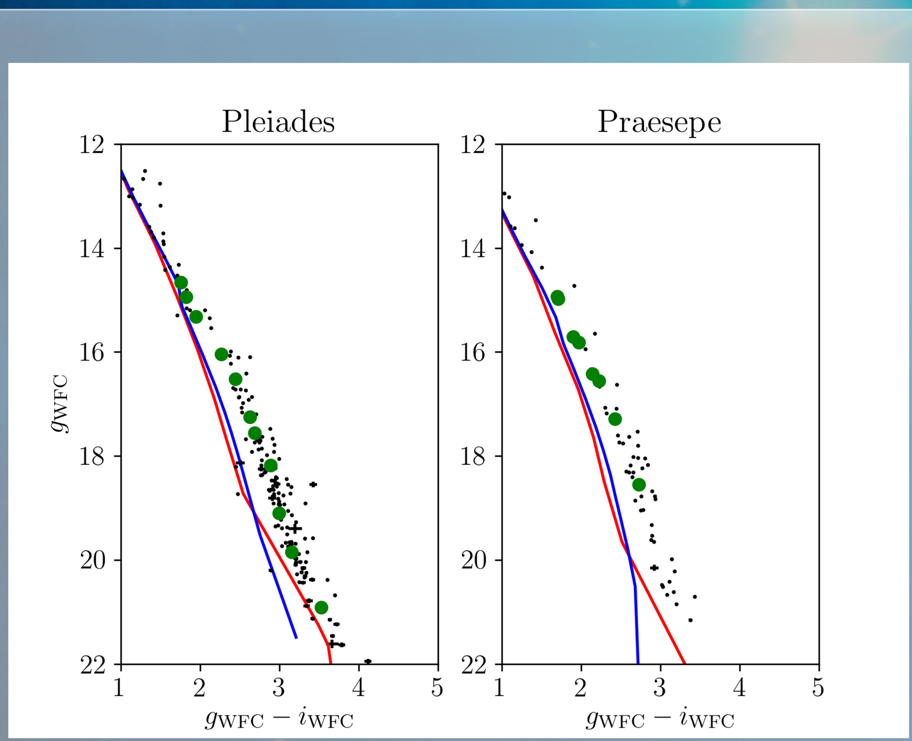

Figure 1 - The Baraffe (2015) (red) and Dotter et al. (2008) (blue) isochrones for the Pleiades (left) and Praesepe (right), plotted with photometric data. The 20 spectroscopic targets are overlaid in green.

2. Spectral Energy Distribution Fitting

The distance and extinction of the Pleiades and Praesepe clusters is well constrained, so we can make a robust estimate of the radius of each target from the fit.

For the fitting process, we use ACAM photometry, through the g, r, and i filters, to cover the optical, 2MASS and UKIDSS (where available) to cover the near Infrared and WISE and Spitzer IRAC (where available) to cover the mid-IR.

Figure 2 shows that coverage of this photometry allows us to confidently fit from blueward of the blackbody peak to the Rayleigh-Jeans tail; providing a thorough characterisation of the SED and hence a luminosity and SED temperature for each star.

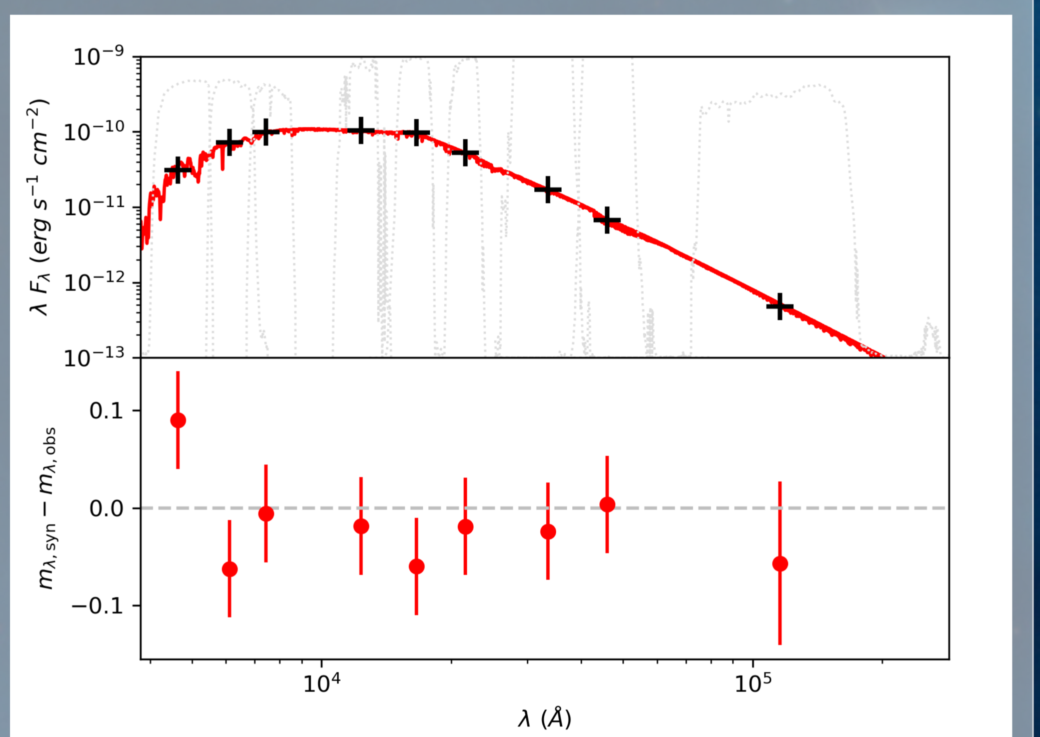

Figure 2 - **Top**: An example model SED (red) resulting from fitting the photometric data points (black). **Bottom**: The residuals from the fit are shown. The formal uncertainties are often too small, so we floor the uncertainties at 0.05 mag.

Figure 3 shows the radii that we estimate from the luminosity and SED temperature compared to the theoretical isochrones. There is a clear inflation in radius of at least 10% when compared to the models.

The SED temperatures (T_{SED}) are considerably cooler than those predicted at that luminosity from the isochrones. There is a second measure of temperature using the lines and bands in the spectra (T_{SP}) and if these are consistent with T_{SED}, this would be a powerful confirmation of the radius inflation. We carry out this comparison in the next two sections.

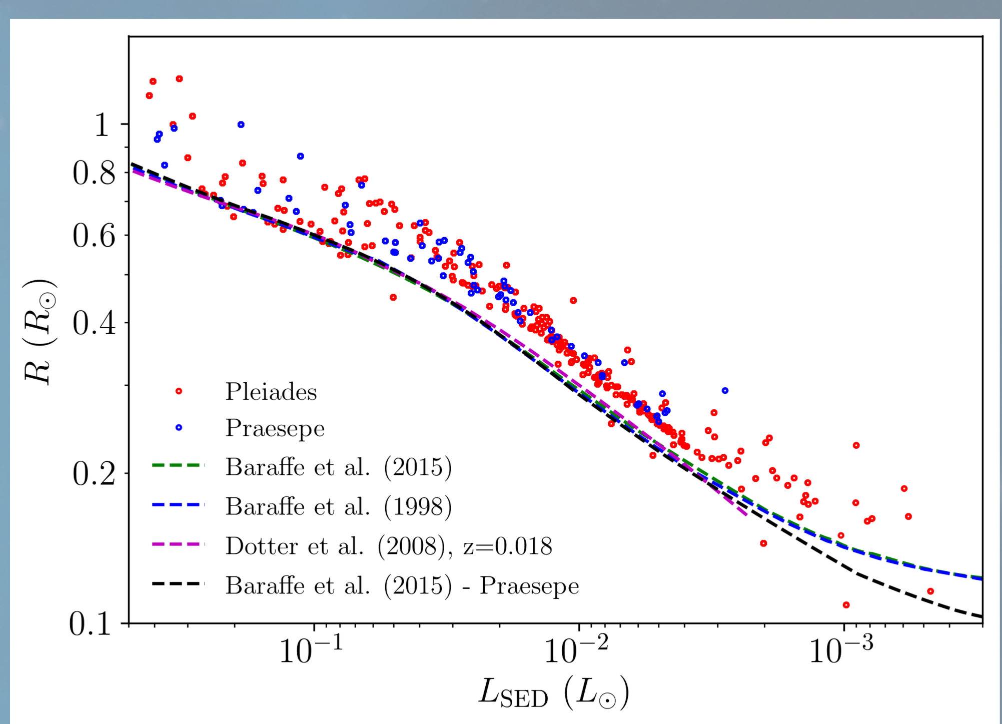

Figure 3 - The radius vs luminosity plot resulting from SED fitting. The theoretical isochrones of Baraffe et al. (1998, 2015) and Dotter et al. (2008) are included for comparison. The observational sequence exhibits radii that are at least 10% larger than the equivalent model.

3. Spectroscopic Data

To determine the spectroscopic temperature of each star, we used spectra captured using ACAM on the William Herschel Telescope. Narrow-slit spectra have a better signal to noise than wide-slit spectra, but lose flux. So, for each target we took a narrow-slit observation, and a subsequent wide-slit observation to obtain a wavelength-dependent flux normalisation to impose upon the narrow-slit spectrum. To flux-calibrate them, flux standard stars were observed at regular intervals throughout the observing run. Telluric absorption was also removed using **molecfit** (Smette et al 2015, Kausch et al 2015).

To improve the fluxes further, we performed a correction using deep photometry. This yielded fluxes good to 1 - 5%, demonstrated in **Figure 4**.

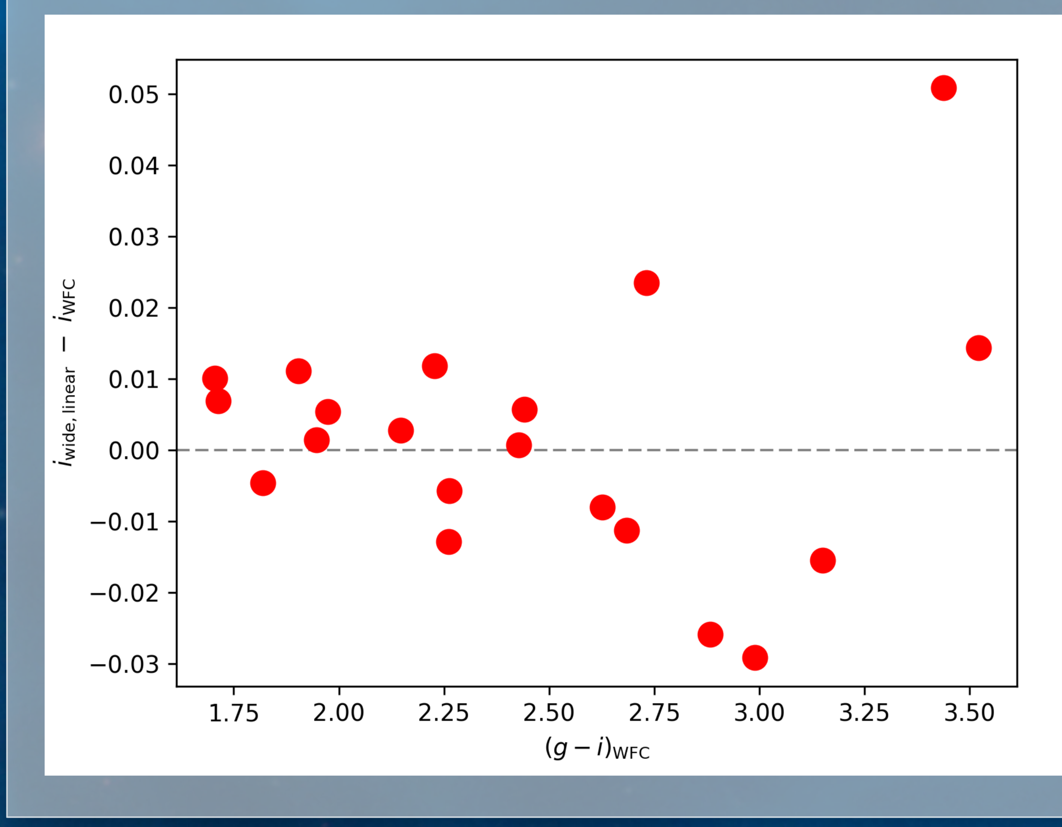

Figure 4 - The residual of the final flux calibrated, corrected spectroscopy folded through the i_{WFC} system response to yield synthetic photometry compared to the corresponding i_{WFC} photometry.

The formal uncertainties for each data point are much larger than the residual, therefore they are not shown. Using this method, we achieve residuals between spectra and data with an RMS of 1.73%.

4. Comparison

Figure 5 shows that the temperatures determined from the SED better match the spectra than those predicted from the isochrone at the observed luminosity.

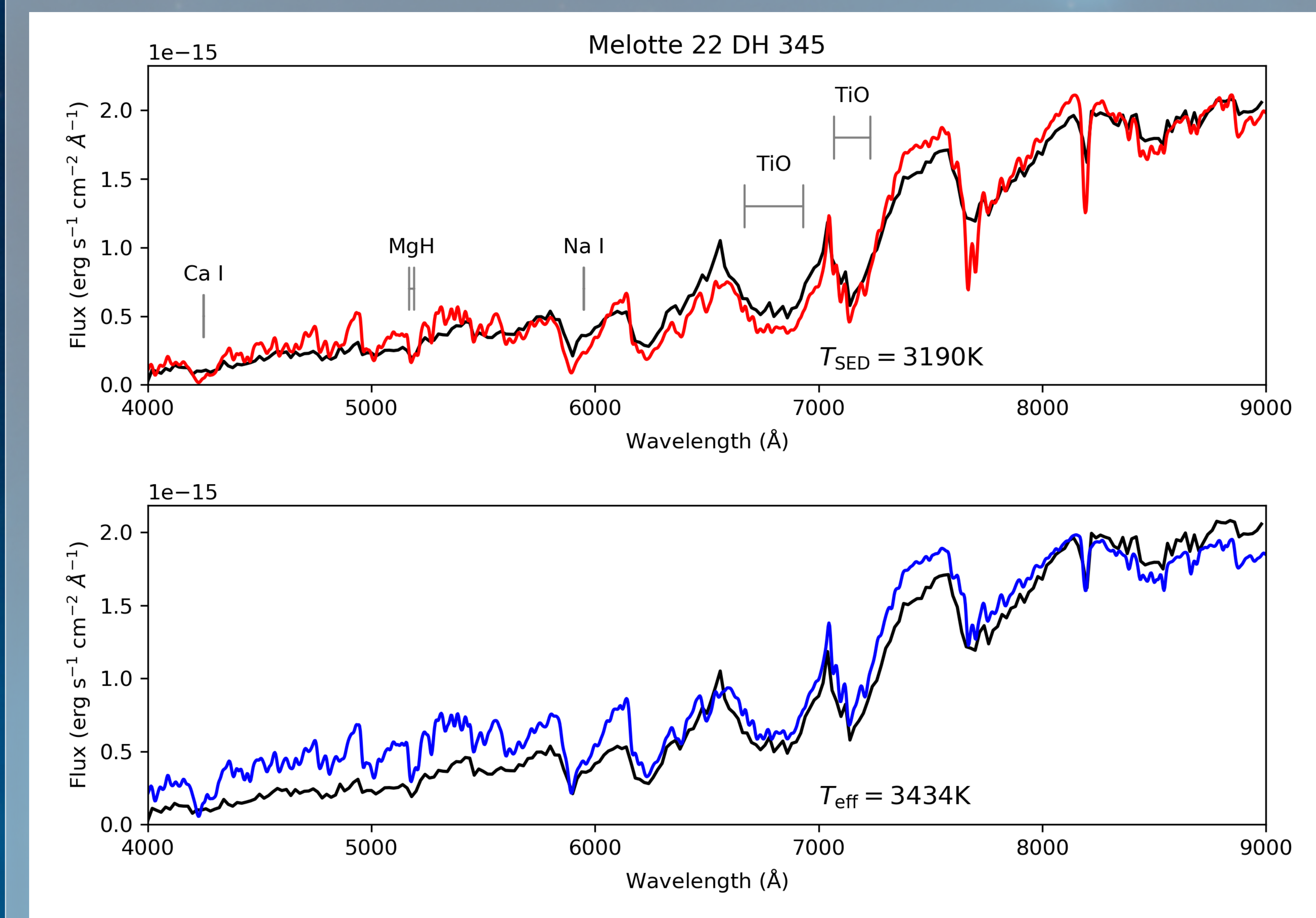

Figure 5 - The flux calibrated observed spectra (black) plotted under the model spectrum generated from the temperature determined from our SED fitting at the top (red) and the Pleiades age isochronal model that best fits the SED at the bottom (blue).

Figure 5 shows that the cooler temperature determined from the SED fitting is also a better fit to the spectra than the isochronal temperature. Specifically the continuum and lines shortward of 6500Å, are reproduced better, though there are still significant differences.

5. Conclusion

We have presented a sample of stars from the Pleiades and Praesepe for which we have determined the temperatures using SED fitting and optical spectroscopy. Both give temperatures significantly cooler than those predicted by the isochrone. Furthermore, both support the conclusion that the radii of the stars in the sample require inflation by at least 10% compared with the isochrones.

References and Acknowledgments

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