Observation vs. theory: testing the synthetic IR colours of young very low mass stars/brown dwarfs using the evolutionary tracks

Jonathan Tottle[1], Subhanjoy Mohanty

Astrophysics Group, Imperial College London, UK

Abstract

We test synthetic spectra as well as evolutionary models of young very low-mass stars (VLMS) and brown dwarfs (BDs) by comparing empirical IR colours of Pre-Main Sequence (PMS) objects with widely used stellar models. We find that the temperatures of early as well as late M types implied by the synthetic spectra are several hundred Kelvin cooler than expected from the standard PMS spectral type-T_{eff} conversion. As a result, derived temperatures of objects from the nearby star forming region Chameleon I diverge strongly with those expected from the theoretical evolutionary tracks for their known age. We conjecture that the problem is due to combined H_2O and dust opacity uncertainties in the synthetic spectra; in particular, that dust effects are being underestimated at later types.

Why use stellar models?

Evolutionary and atmospheric models have long been used in an attempt to characterise stellar properties. In the case of single PMS objects, they are often the only indicator of (sub)stellar status.

Why look at young M types?

For very young (~2-10Myr) objects, the M spectral type encompasses almost two orders of magnitude in mass: from the lowest mass BDs to roughly solar type stars. The ability to properly categorise them is thus essential to our knowledge of the physics of star formation.

Converting spectral types to effective temperatures using evolutionary models

Using the standard Main Sequence conversion scale to convert spectral types to temperatures for very young stars is problematic. By using the *evolutionary models* and enforcing coevality in separate components of multiple systems, Luhman et al. (2003) redefined the spectral type-T_{eff} scale using spectral types and luminosities of young objects. We refer to these temperatures as T_L.

Why use atmospheric models?

We can use synthetic spectra produced by atmospheric models to infer an object's temperature by matching its spectrum. By fitting synthetic spectra to PMS templates, it is possible to redefine the spectral type-T_{eff} scale from the *atmospheric models* (which we denote as T_A). We can then compare this with the evolutionary model temperature scale to test the models against each other.

Results I – PMS spectral type-T_{eff} scale from synthetic spectra

Atmospheric Models

We use the latest version of synthetic spectra generated with the PHOENIX code, namely the AMES-Cond/Dusty models (Allard et al. 2001) and the BT-Settl models (Allard et al. 2012). The former two have long been used to model low-mass objects, whilst the latter has recently been shown to be better fit NIR Main Sequence observations.

Data

We use the Luhman et al. (2010) PMS IR spectral template colours, derived from the bluest (least extincted/diskless) young objects from nearby star forming regions/stellar associations.

Fitting

For each spectral subclass, we perform an RMS goodness of fit across the NIR/MIR bands for every temperature. This is done for each atmospheric model; see Fig. 1 for an example fit.

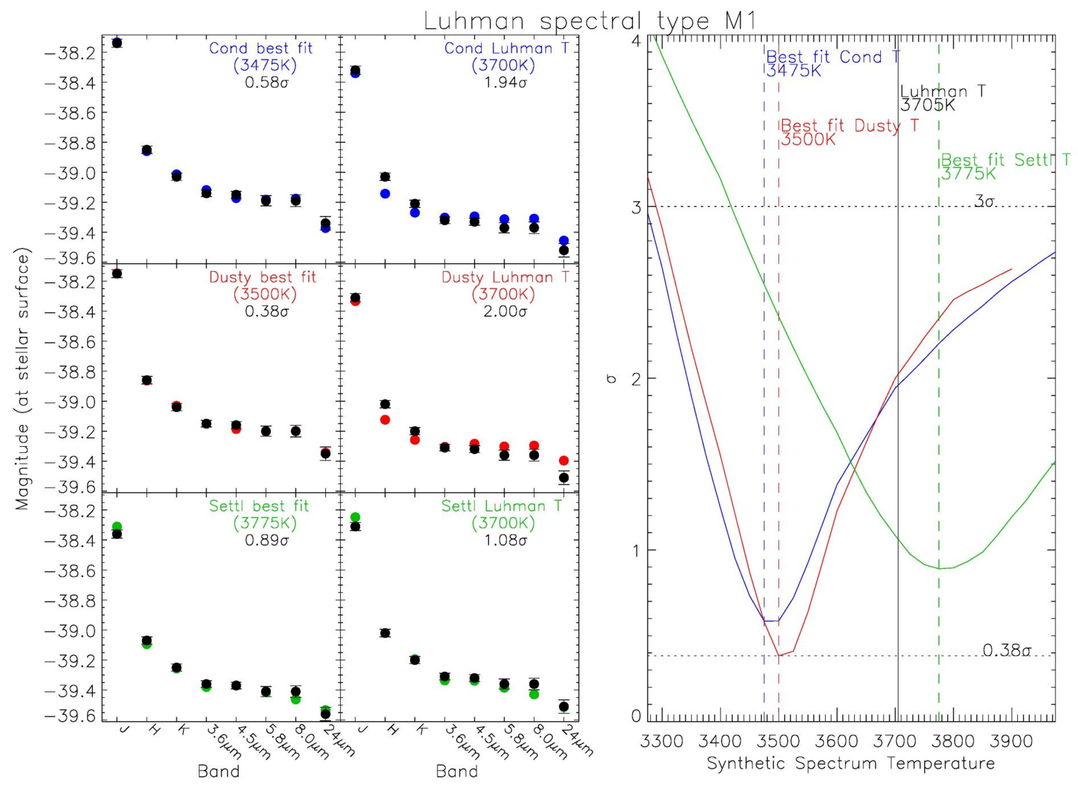

Figure 1: Example of a fit to a spectral subclass (M1). On the left are the photometric best fits at any temperature and at T_L for each model (AMES-Cond in blue, AMES-Dusty, in red and BT-Settl in green) compared with the PMS template (black). On the right is the RMS value for each model as a function of temperature, along with an indication of the Luhman temperature (from the evolutionary models).

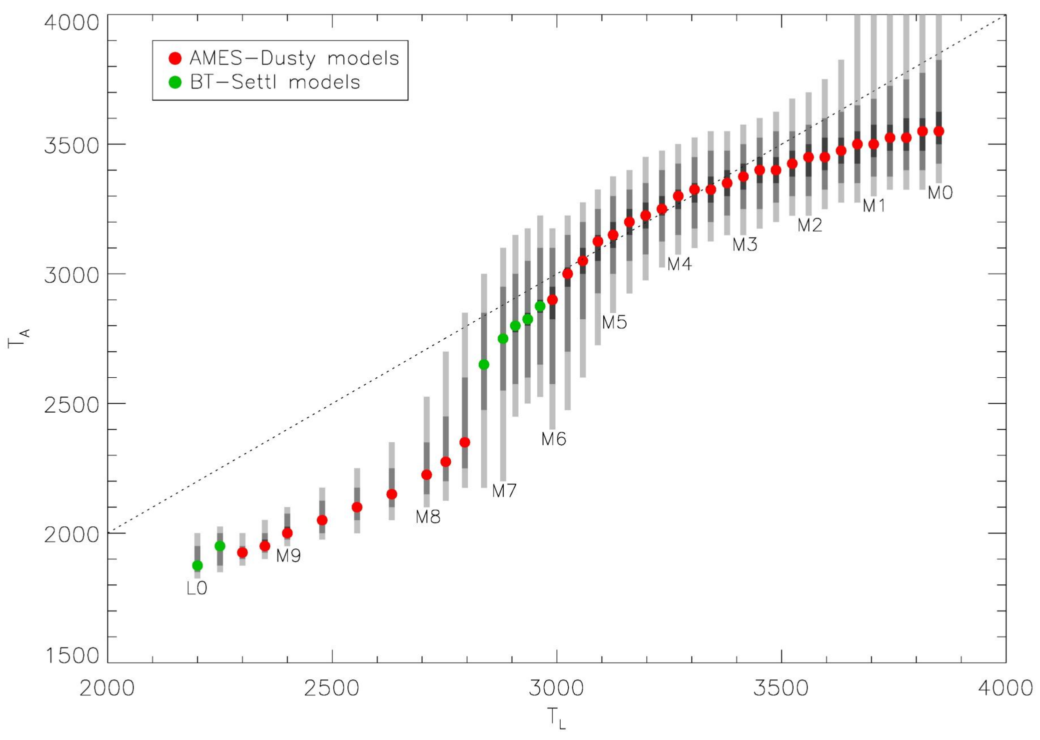

Figure 2: T_A (atmospheric scale) vs. T_L (evolutionary scale) for the spectral range considered here. The dark, medium and light grey error bars denote the temperature range for fits under 1σ, 2σ and 3σ respectively. The best fit model type is denoted by colour.

We use the best fitting synthetic spectrum for each spectral subclass to derive a new spectral type-T_{eff} scale, based on the atmospheric models. We compare this scale (T_A) to the temperature scale derived by Luhman from the evolutionary models (T_L) in Fig. 2. We find:

- The best fits (which come mostly from AMES-Dusty), T_A, are cooler than T_L by up to ~300K and ~500K in the early and late M types, respectively.
- In the early types, for the synthetic spectra at T_L (Fig. 1), BT-Settl is always the better fit as the discrepancy arises from solely from the J band, whereas AMES-Cond/Dusty are poorly fit in almost every band.
- In the late types, for the synthetic spectra at T_L (not shown here), AMES-Cond is completely incorrect (as it neglects atmospheric dust), whilst AMES-Dusty and BT-Settl give comparable fits.

Results II – H-R Diagram for young objects

78 class III (disk-less) M-type objects were selected from Chameleon I (distance ~165pc, age ~2-3Myr). All have previously been assigned *J*-band extinctions from the optical, temperatures (from the spectral type-T_L scale) and luminosities (from *J*-band empirical bolometric corrections) in Luhman (2004, 2007).

We derive extinctions using the NIR by matching to the PMS templates, and temperatures are assigned to each object using the spectral type-T_A scale. Radii are found by scaling the synthetic spectra flux to the observed *J* band flux, and luminosities from $4\pi R^2 \sigma T^4$. Our luminosities and temperatures (known as 'Allard properties') are compared to the Luhman properties on a H-R diagram (Fig. 3).

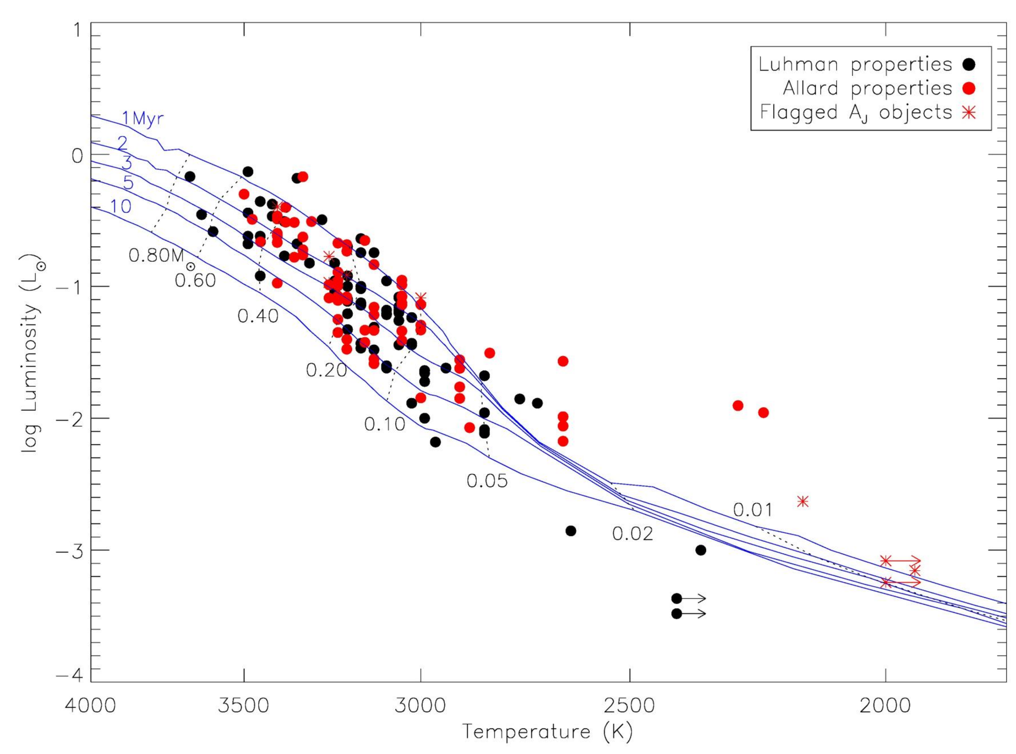

Figure 3: H-R diagram for our two sets of parameters (the 'Luhman' properties derived from evolutionary tracks and the 'Allard' from the synthetic spectra). Extinctions which differ from Luhman's derivations by >0.5 mags, or are poorly fit to the templates, have been flagged. The Baraffe et al. (1998) and Chabrier et al. (2000) evolutionary tracks are shown in blue, with indicated masses and ages.

From Fig. 3, we find:

- The luminosities between these two sets of parameters are quite similar, due to the flat bolometric corrections across the M types, as well as the synthetic bolometric corrections matching the empirical ones.
- The discrepancies between T_L and T_A seen in the previous section cause the later type objects to float above the tracks, suggesting they are all extremely young objects. In the earlier types the discrepancy is harder to observe, both due to the small number of early M types in the sample, and the fact that in the evolutionary tracks the luminosities don't vary much for a ~200K change in temperature.

Conclusions

There are three possible explanations for the observed T_A-T_L discrepancy:

1. The PMS spectral templates are incorrect, which can be caused by residual extinction. However, this should be independent of spectral type, whereas we only find issues in the early/late M types.
2. The spectral type-T_L scale is wrong due to inaccuracies in the evolutionary models; the tracks ignore magnetic activity, which is known to have an affect on stellar evolution. However, activity in the M types appears to cause T_{eff} offsets from the tracks of order ~100 K (Morales et al. 2008, Mohanty and Stassun 2012), much less than the ~500 K discrepancy we observe in the late types here.
3. The spectral type-T_A scale is wrong, which implies there are inaccuracies in the synthetic spectra. Indeed, there are deviations in the NIR between models and observations at both the K-M and M-L transitions in the Main Sequence (Allard et al. 2012), similar to what we have found here.

We conjecture that the third suggestion is the main cause for the observed discrepancy. We further postulate:

- Although AMES-Dusty is a superior fit throughout the M types, the BT-Settl spectra at the temperatures we expect from the evolutionary models (T_L) are in general better; in the early types they are only encumbered by a poor *J* band fit. Perhaps the improvements made in the years between AMES-Dusty and BT-Settl have been the right direction, with another small amendment necessary.
- For the hottest objects (the earliest types), the discrepancy in the BT-Settl *J* band may be caused by slightly incorrect H^- or H_2^- opacities, perhaps related to remaining abundance uncertainties. These objects are too hot to be affected by incorrect H_2O opacities.
- At the cooler end of the scale, we suggest neglected dust effects are to blame; dust causes reddening both by H_2O destruction (due to backwarming) and absorption of shorter wavelengths. The effect of dust being underestimated could be due to uncertainties in the size, shape and/or structure of the grains; increasing its effects will act to make the models redder, in line with observations.

References

Allard, F.,Hauschildt, P. H., Alexander, D. R., Tamanai, A., & Schweitzer, A. 2001, ApJ, 556, 357

Allard, F., Homeier, D., & Freytag, B. 2012, EAS 57:3-43

Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, A&A, 337, 403

Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. H. 2000, ApJ, 542, 464

Luhman, K. L., Stauffer, J.R., Muench, A. A., Rieke, G. H., Lada, E. A., Bouvier, J., & Lada, C.J. 2003, ApJ, 593, 1093

Luhman, K. L. 2004, ApJ, 602, 816

Luhman, K. L. 2007, ApJS, 173, 104

Luhman, K. L., Allen, P. R., Espaillat, C., Hartmann, L., & Calvet, N. 2010, ApJS, 186, 111

Morales, J. C., Ribas, I., & Jordi, C. 2008, A&A, 478, 507

Mohanty, S., & Stassun, K. G. 2012, ApJ, 758, 12

Science & Technology Facilities Council

Imperial College London

[1] j.tottle11@imperial.ac.uk