Pre-Main-Sequence Stars: Older Than We Thought?

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Abstract

We have derived ages for several young (< 30 Myr) pre-main-sequence (pre-MS) clusters. These ages are up to a factor two older than previous derivations, a result with wide ranging implications, including that protoplanetary discs survive significantly longer than currently believed. Our ages were derived using a set of semi-empirical pre-MS isochrones that incorporate an empirical colour-$T_{\rm eff}$ relation and bolometric corrections based on the K_s-band luminosity of Pleiades members, with theoretical corrections for the dependence on log g. We find that the pre-MS ages are in broad agreement with main-sequence (MS) ages derived from high-mass members.

Pre-main-sequence isochrones: the Pleiades benchmark

In Bell et al. (2012; see QR code above) we presented a critical assessment of commonly used pre-MS isochrones by comparing them to well-calibrated colour-magnitude diagrams (CMDs) of the Pleiades (see Fig. 1). We found the following.

- Photometric calibration of pre-MS stars using MS standards can place the pre-MS in the wrong position in CMDs. This effect can be as large as 0.15 mag in (g-i), resulting in an error in age of a factor 2.
- Isochrones should be transformed into the natural photometric system of the observations, rather than transforming both models and data to a standard system.
- For $T_{\rm eff}$ < 4000K the models overestimate the flux in the optical, predicting colours that are too blue for a given mass (see Fig. 1).

In this paper we used the interior models of Baraffe et al. (1998), D'Antona & Mazzitelli (1997), Siess et al. (2000), and Dotter et al. (2008). The atmospheric models were the BT-Settl models of Allard et al. (2011).

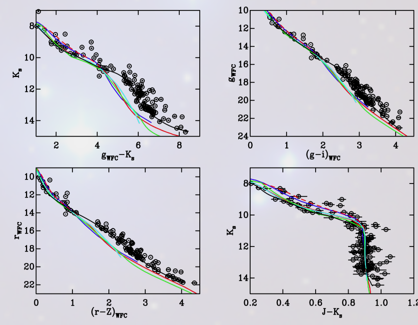

Fig. 1. Optical/near-IR CMDs of the Pleiades. The 130 Myr isochrones of BCAH98 α=1.9 (red, continuous), BCAH98 α=1.0 (red, dashed), SDF00 (blue), DAM97 (green) and DCJ08 (cyan) are overlaid, adopting a distance modulus dm=5.63 and a reddening $E(B-V)$=0.04. The black line is the spline fit (by-eye) to the Pleiades single-star sequence. Top left: K_s, $g_{\rm WFC}$-K_s. Top right: $g_{\rm WFC}$, $(g-i)_{\rm WFC}$. Bottom left: $r_{\rm WFC}$, $(r-Z)_{\rm WFC}$. Bottom right: K_s, J-K_s.

Quantifying the discrepancy

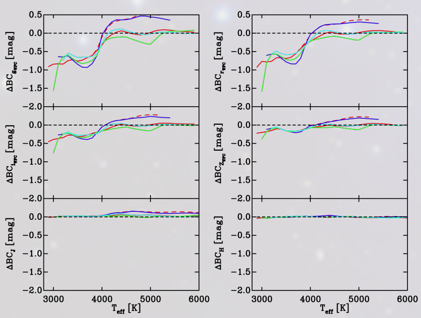

Fig. 2. Model dependent corrections (ΔBC) calculated as a function of $T_{\rm eff}$ for the optical $(griZ)_{\rm WFC}$ and near-IR JH bandpasses. Line types are as in Fig. 1.

To quantify the mismatch between the models and data as a function of $T_{\rm eff}$ in a given photometric bandpass, we identified a bandpass where this difference was minimal. Our analysis was as follows.

- We used a sample of MS binaries with photometric observations in optical and near-IR bandpasses.
- We calculated system magnitudes from the model isochrones.
- We compared the two across a significant mass ($T_{\rm eff}$) range.

We found that the K_s-band magnitude is the most reliably predicted by the model isochrones. Hence we used the K_s-band luminosity of Pleiades members to estimate $T_{\rm eff}$, and quantify the overestimation in flux (see Fig. 2). These define an empirical, model-dependent adjustment to the theoretical bolometric corrections and colour-$T_{\rm eff}$ relation at an age of 130 Myr required to fit the observed Pleiades sequence.

Semi-empirical pre-main-sequence isochrones: revised ages

We assume that the *absolute* adjustment to the bolometric corrections and colour-$T_{\rm eff}$ relation required for the Pleiades is valid for *all* ages. We fitted the pre-MS population of our six clusters (χ Per, λ Ori, NGC 1960, NGC 2169, NGC 2362, and NGC 7160) using the τ^2 fitting statistic of Naylor & Jeffries (2006), adopting an intrinsic binary fraction of 50% (see Fig. 3).

If we adopt the pre-MS ages derived using the BCAH98 α=1.9 models, our revised ages are **λ Ori ~ 11 Myr, NGC 2169 ~ 11 Myr, NGC 2362 ~ 11 Myr, χ Per ~ 15 Myr, NGC 7160 ~ 16 Myr, and NGC 1960 ~ 19 Myr**.

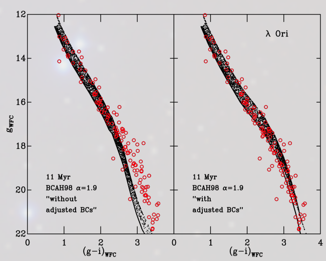

Fig. 3. Spectroscopically confirmed members of the λ Ori star-forming region from Bayo et al. (2011). Overlaid are 11 Myr BCAH 98 α=1.9 isochrones, using a distance modulus of dm=8.02 and reddening $E(B-V)$=0.11.

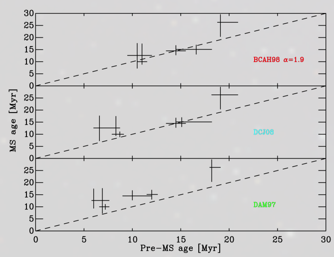

Fig. 4. The MS versus pre-MS ages for our sample of clusters.

These ages are up to a factor 2 older than previous determinations. We find, however, that these ages are consistent with ages we have derived from the MS using the techniques of Naylor (2009; see Fig. 4).

We intend to extend this study into the < 10 Myr regime, where we have photometry for an additional eight clusters (Cep OB3b, IC 348, IC 5146, NGC 2244, NGC 6530, NGC 6611, the ONC, and σ Ori).