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Ages and age spreads in young stellar clusters

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Abstract. I review progress towards understanding the timescales of star and cluster formation and of the absolute ages of young stars. I focus in particular on the areas in which Francesco Palla made highly significant contributions – interpretation of the Hertzsprung-Russell diagrams of young clusters and the role of photospheric lithium as an age diagnostic.

Key words. Stars: abundances – Stars: evolution – Stars: ages – Galaxy: open clusters and associations

1. Introduction

Estimating the absolute ages of young stars and ascertaining the extent of age spreads in young clusters is crucial in understanding the mechanisms and timescales upon which stars form, upon which circumstellar disks disperse and planetary systems assemble, and for understanding the role of varying stellar birth environments on these issues. Francesco Palla produced highly influential work in these areas; my review focuses on two key aspects: (i) the interpretation of the Hertzsprung-Russell diagrams (HRDs) and colour-magnitude diagrams (CMDs) of young clusters and star forming regions (Palla & Stahler 1999, 2000, 2002), and (ii) the use of photospheric lithium abundance measurements as an orthogonal method to estimate and calibrate young stellar ages (Palla et al. 2005, 2007; Sacco et al. 2007).

2. Ages from H-R diagrams

Low-mass stars ($\leq 2M_{\odot}$) take significant time ($\sim$ 10–200 Myr) to evolve from newly revealed T-Tauri stars to the zero-age-main-sequence (ZAMS). This pre-main-sequence (PMS) evolution occurs on mass-dependent timescales (faster for higher mass stars); stars initially descend fully convective Hayashi tracks followed by, for higher mass objects ($\geq 0.4M_{\odot}$), the development of radiative cores and a blueward traverse along the Henyey track before settling onto the ZAMS (e.g. Iben 1965). In principle, the construction of grids of mass-dependent evolutionary tracks and corresponding isochrones in the HRD can be used with estimates of luminosity and effective temperature ($T_{\rm eff}$) or equivalently (given appropriate bolometric corrections), absolute magnitude and colour, to yield ages and masses for PMS stars. An advantage to using low-mass stars when studying young clusters, rather than their higher mass siblings, is they are much more populous, allowing statistical analyses, and their movement in the HRD can be much larger for a given age change.

In a series of papers, Francesco (and Steven Stahler) noted that, when plotted on the HRD, stars are dispersed around the single isochrones predicted by PMS models. This indicated a substantial age spread of at least a few Myr, and in some cases $>$ 10 Myr. The pattern was repeated in several young clusters and when ages inferred from HRD position were turned into a star formation history, suggested an accelerating star formation rate as a function of (linear) time. This highly-cited result has launched a thousand telescope proposals and is still hotly debated. Does an extended star formation history indicate inefficient star formation moderated by turbulence and magnetic fields, or can the spreads be explained by observational uncertainties and problems with PMS models so that actually, star formation is rapid and efficient, taking place on dynamical timescales?

Opponents of the idea of large age spreads have pointed to the role of astrophysical effects and observational uncertainties in scattering stars in the HRD, giving the *impression* of a large age dispersion. Hartmann (2001) noted that the apparent age distribution was lognormal, with $\sigma \sim 0.4$ dex, perhaps reflecting the logarithmic nature of uncertainties in luminosity estimates and that age $\propto L^{-3/2}$ on Hayashi tracks. There are uncertainties in distance, extinction, and also due to intrinsic variability, accretion and the presence of binaries that must certainly be accounted for in estimating a true age dispersion. Detailed simulations by Reggiani et al. (2011) and Preibisch (2012) concluded that whilst these effects were important, they probably do not explain the entire extent of observed dispersions.

It seems certain that the very old ages assigned to at least some PMS stars in young clusters are due to mis-estimated luminosities and temperatures associated with an incorrect or at least incomplete treatment of extinction and accretion (Manara et al. 2013). On the other hand, support for genuine dispersions in luminosity (or radius at a given $T_{\rm eff}$) has been found by considering the distribution of projected radii (rotation period multiplied by projected rotation velocity) in the Orion Nebula cluster (ONC) and IC 348 (Jeffries 2007; Cottaar et al. 2014) and from the IN-SYNC APOGEE survey that finds a significant correlation between increasing age and spectroscopic gravity in the same clusters (Cottaar et al. 2014; Da Rio et al. 2016).

There seems little doubt that a fraction of the observed age dispersion must be due to sources of astrophysical and observational uncertainty, but also strong evidence that at least some of the luminosity and radius spread is real. Whether this implies genuine age spreads requires evidence from other observations and independent astrophysics.

3. Lithium as an age indicator

Lithium is ephemeral in low-mass stellar photospheres. As PMS stars contract, their cores reach Li-burning temperatures before reaching the ZAMS. If the convection zone base is also above the Li-burning temperature (which it would be in fully convective stars) then photospheric Li is also depleted on timescales less than a few Myr. The age at which core Li burning begins is mass-dependent (later for lower mass stars), but the development of a radiative core can arrest photospheric Li depletion in more massive objects. These phenomena lead to a complex, but age-dependent, behaviour for Li abundance as a function of luminosity, $T_{\rm eff}$ or colour.

Palla et al. (2005, 2007) were among the first to suggest Li depletion could serve as an independent test of ages in very young low-mass stars. Li depletion is expected to begin in stars of $\sim 0.5 M_{\odot}$ at an age of about 5 Myr and subsequently develops at higher and lower masses. Since the physics of Li depletion is comparatively simple, it has been argued that this currently provides the *least* model-dependent means of estimating young stellar ages (e.g. Soderblom et al. 2014), however masses cannot be measured directly so one relies on colours, $T_{\rm eff}$ or (better) luminosities as proxies.

Palla et al. (2005) and Sacco et al. (2007) found examples of Li-depleted low-mass stars that appeared older than 10 Myr in the ONC and the σ Ori cluster, and much older than the bulk of their siblings, perhaps supporting the notion of large age spreads $>$ 10 Myr. Subsequent work by Sergison et al. (2013) on the ONC and NGC 2264 confirmed the presence of a dispersion in Li abundance, but noted the difficulty in assessing Li abundances for

PMS stars that are often accreting. Any veiling continuum weakens the Li I 6708Å line that is exclusively used; this combined with the saturated nature of this strong resonance line can lead to the mistaken inference of significant Li depletion. Lim et al. (2016) took the expedient option of excluding stars with signs of accretion from their analysis (which one might presume were younger stars), still finding evidence for some age dispersion in NGC 2264, but with an absolute value ≤ 4 Myr and smaller than the spread implied by the HRD.

Taken at face value, the combined information from Li depletion, the HRD and spectroscopic indicators of radii suggests that some dispersion in age is present, but probably no more than a few Myr and not as much as suggested by the HRD alone. However, there are problems that have emerged even with this simple interpretation that may betray interesting facets of PMS evolution that have yet to be correctly incorporated.

4. Problems with evolutionary models

(i) *Why is Li depletion correlated with rotation?* That rapidly rotating low-mass stars appear to preserve their Li longer, has been established in older clusters and becomes clearer with better data (Barrado et al. 2016). This trend is now becoming apparent at even younger ages and may be responsible for some of the Li depletion dispersion previously claimed to be associated with an age spread (Bouvier et al. 2016). Since PMS stars are expected to spin-up as they contract, then older stars ought to be faster rotating and *more* Li depleted if the age dispersion were genuine.

(ii) *Why do Li-depletion ages disagree with isochronal ages from the HRD?* Jeffries et al. (2017) have pointed out that Li depletion ages and HRD/CMD ages are not completely independent; Li depletion takes places when the core temperature, and hence mass to radius ratio, reaches a certain threshold, whilst HRD/CMD ages also depend on radius at a given $T_{\rm eff}$, though not as sensitively. The *same* evolutionary models give significantly younger ages for low-mass PMS stars in the γ^2 Velorum cluster than implied by the strong Li depletion seen in its M-dwarfs. The Li depletion also takes place at much redder colours and lower inferred $T_{\rm eff}$ than expected. The CMD and Li-depletion pattern cannot be explained simultaneously by any commonly used evolutionary codes at any age.

(iii) *Why are more massive stars in young clusters judged to be older than the low-mass stars?* The ages of clusters with PMS stars can also be estimated by looking at how far from the ZAMS towards the terminal-age main-sequence their high mass ($> 5M_\odot$) stars have progressed. When done with a self-consistent and accurate treatment of reddening Naylor (2009) suggested that the high-mass stars were significantly older than their low-mass siblings by a factor of two. This was followed-up with a larger sample by Bell et al. (2013), who demonstrated that the low-mass ages could be brought into agreement with the high-mass ages (and ages from Li depletion) with systematic changes in the bolometric corrections adopted by the models.

(iv) *Why do current models fail to correctly predict the location of PMS eclipsing binary components in the HRD?* New examples found in star forming regions provide challenges to evolutionary models. Their masses and radii are not well predicted from their estimated luminosities and $T_{\rm eff}$ (Kraus et al. 2015; David et al. 2016). The PMS binary components appear colder than predicted by the models and more luminous than predicted at the age of higher mass stars in the same clusters.

These problems have lead to consideration of whether PMS evolutionary models are yielding the correct absolute masses, ages and hence age spreads at all. An idea that has gained some traction is that episodic accretion during the first million years of a star's life can significantly influence both the HRD position

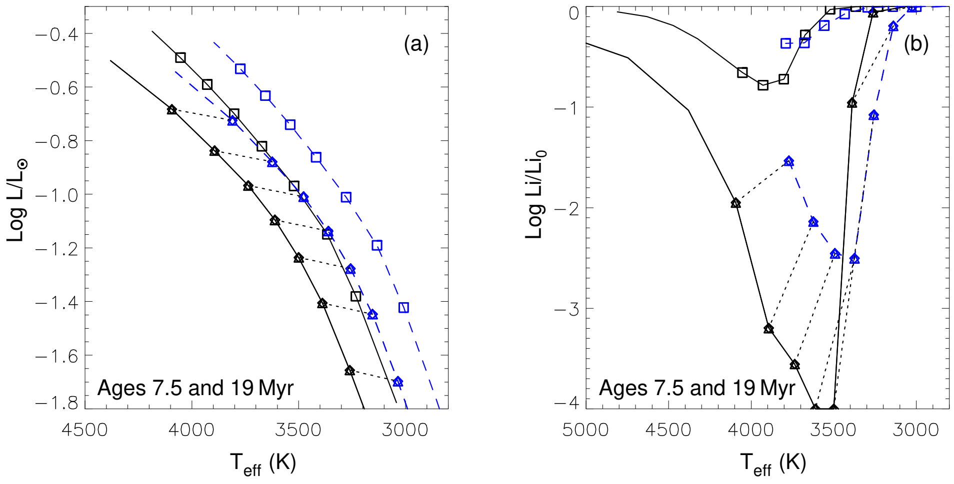

Fig. 1. The effects of 10% inflation due to magnetic activity. The left hand panel shows isochrones in the HRD from Baraffe et al. (2015) at 7.5 (diamonds) and 19 Myr (squares). The dashed lines show the same isochrones modified for the effects of radius inflation. Mass points from $0.2M_\odot$ to $0.8M_\odot$ in $0.1M_\odot$ steps are indicated by open symbols on each isochrone. The dotted lines indicate the movement of a star of a given mass due to radius inflation. Note how an inflated 19 Myr isochrone lies almost on top of the 7.5 Myr uninflated isochrone. The right hand panel is similar but shows the effects of radius inflation on the expected level of Li depletion. These diagrams (adapted from Jeffries et al. 2017 by R. Jackson priv. comm.) illustrate that radius inflation acts to reduce luminosity, lower $T_{\rm eff}$ and decrease Li depletion for a star of a given mass and age.

and Li depletion (Baraffe & Chabrier 2010; Baraffe et al. 2017). Variations in accretion rate and the exact timing of accretion could lead to apparent age dispersions and to the occasional star appearing much older in the HRD and/or exhibiting significant Li depletion.

An alternative that is also gaining support is that magnetic activity may "inflate" low-mass stars (or at least slow their contraction), either through magnetic inhibition of convection (Mullan & MacDonald 2001; Feiden & Chaboyer 2014) or the blocking of radiative flux by cool starspots (Jackson & Jeffries 2014; Somers & Pinsonneault 2015a). These ideas have the attraction that we know young low-mass stars are magnetically active and that they have extensive starspot coverage (some recent spectroscopic estimates suggest more than 50%, Gully-Santiago et al. 2017).

Let us suppose then that active low-mass PMS stars are inflated by ~ 10% compared to the predictions of "standard" evolutionary models at a given mass and age. This is roughly the level suggested by recent modelling work that attempts to incorporate the effects of suppressed convection or starspots. Jeffries et al. (2017) (see also Feiden 2016; Messina et al. 2016) have shown that such stars become cooler and only slightly less luminous. The net result is that stars move almost horizontally in the HRD resulting in severely underestimated ages and masses when using "standard" models (see Fig. 1). At the same time their core temperatures are reduced, delaying the onset of Li depletion and decreasing the $T_{\rm eff}$ of stars in which Li depletion is first seen.

If magnetic models such as those of Jackson & Jeffries (2014), Somers & Pinsonneault (2015b) or Feiden (2016) are adopted, then HRD/CMD ages are brought into much closer agreement with the Li depletion ages, but at the expense of *doubling* the ages inferred from the HRD (see Fig. 1). This also brings ages from low-mass and high-mass stars into broad agreement, potentially solves the problems with eclipsing binary parameters (MacDonald & Mullan 2017) and could introduce a dispersion into the HRD and Li-depletion patterns of young stars that is correlated with rotation and/or magnetic activity (Somers & Pinsonneault 2015b). If correct, such a large shift has considerable implications for the timescales of PMS evolution, the dispersal of circumstellar matter and hence the time available to form planetary systems, all of which are keyed-in to the absolute timescales set by age estimates for young, low-mass stars.

5. Summary

The investigation of ages and age spreads in young clusters using the HRD and Li-depletion, begun by Francesco Palla and colleagues, remains a vibrant and controversial topic. Current evidence suggests that age spreads are a lot smaller than 10 Myr (within a single cluster), but that not all the dispersion in cluster HRD/CMDs and Li depletion can be explained by observational and astrophysical uncertainties. Some of the observed spread does appear to be due to a genuine distribution of radius among stars with similar $T_{\rm eff}$ and mass, which might be attributable to a modest age spread of a few Myr. We are now moving into an era of more sophisticated stellar modelling that questions the veracity of both the absolute ages of PMS stars and the inferred age spreads in young star forming regions.

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