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Applications of the initial to final mass relation: the age of the Galactic halo

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Abstract. Our knowledge of the stellar initial-final mass relation has been transformed in the past decade. Major advances in sensitive wide-field imaging cameras and multiobject spectrographs have led to a "complete" relation, extending down to the lowest mass stars that have burnt their hydrogen given the age of the Universe. This relation now serves as a powerful input into many astrophysical problems. The anchor on the relation at the low mass end, presented by Kalirai et al. (2009), suggests that population II metal-poor stars with t = 12.5 ± 0.5 Gyr are forming white dwarfs today with $M_{\rm final} = 0.529 \pm 0.012\ M_\odot$. Starting with this result, we construct a new relation to derive the age of any population II, metal-poor system based on the present day formation mass of white dwarfs. Applying this method to a small number of kinematically-confirmed Milky Way halo white dwarfs suggests that the local (inner) halo of our Galaxy formed 11.4 ± 0.7 Gyr ago, and is therefore younger than most of the Galactic globular clusters.

Key words. Galaxy: formation – Galaxy: halo – white dwarfs – techniques: spectroscopic

1. Introduction

The initial-final mass relation of stars characterizes the stellar mass loss that is suffered through post main-sequence evolution. The relation directly connects the masses of main-sequence hydrogen-burning stars to their eventual end product white dwarfs. Constraints on the relation are difficult to derive, as they require spectroscopic observations of white dwarfs in stellar systems where the total age is already known (e.g., most notably, star clusters). In these cases, the difference between the total system age and the white dwarf cooling age represents the lifetime of the progenitor star that made the white dwarf, and hence the initial mass of the white dwarf can be calculated.

In the summer of 2001, as I was beginning my PhD thesis, Franca D'Antona and Paolo Ventura hosted me at the Osservatorio Astronomico di Roma in Monte Porzio. The purpose of the visit was to start a new study of the initial-final mass relation of stars, by targeting white dwarfs in rich star clusters that spanned a large range in age. At the time, no constraints on the relation had been established for stars with $M_{\rm initial} < 2.8\ M_\odot$ (i.e., clusters older than the Hyades). We began the process by obtaining ultra-deep, wide-field imaging observations of two dozen star clusters using the Canada-France-Hawaii Telescope, and deriving the fundamental parameters of each

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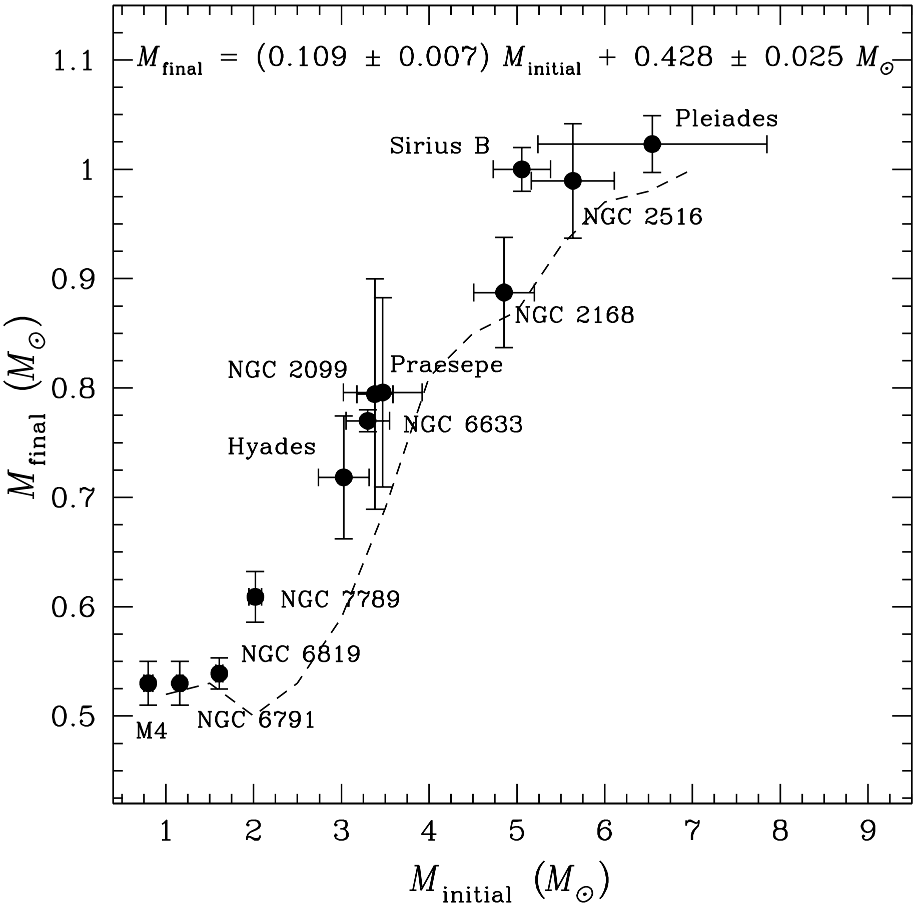

Fig. 1. Initial-final mass relation of stars, based on spectroscopic observations of white dwarfs in open and globular star clusters (Kalirai et al. 2008; and references therein). The data are shown as binned measurements of (typically) several white dwarfs in each star cluster. The results demonstrate that lower mass main-sequence stars produce lower mass white dwarfs, and the relation is now complete down to approximately the lowest mass stars that have had time to evolve given the age of the Universe (Kalirai et al. 2009). A first order fit of the data to a linear relation is illustrated in the panel. This fit includes a gross offset of 0.03 $M_\odot$ to account for the latest white dwarf atmosphere model fits, as described in Tremblay & Bergeron (2009). The dashed curve shows the theoretical prediction of the core mass at the first thermal pulse on the AGB (Girardi et al. 2000). As the core has not yet grown on the AGB, it is expected that this prediction should fall below the measured initial-final mass relation, exactly as seen.

cluster (age, metallicity, reddening, distance). This initial work is summarized in Kalirai et al. (2001a; 2001b; 2001c; 2003), with additional observations reported in Kalirai et al. (2007). Not only did these observations redefine our fundamental knowledge of these valuable star clusters, but they set forth a new multi-object spectroscopic campaign on 8-m and 10-m telescopes to perform the deepest white dwarf spectroscopy to date.

Over the past ten years, several groups have engaged new studies of the initial-final mass relation (Kalirai et al. 2005; Dobbie et al. 2006; 2009; Williams, Bolte, & Koester 2004;

Williams & Bolte 2007; and Williams, Bolte, & Koester 2009). The present status of this work is shown in Figure 1. All of the constraints at the low mass end, including Messier 4, NGC 6791, NGC 6819, and NGC 7789 come from our teams recent work (Kalirai et al. 2007; 2008; 2009). With these new data, we now have a "complete" initial-final mass relation that stretches down to 0.8 $M_{\odot}$ main-sequence stars. A first order fit of the data to a linear relation is shown in Figure 1 (corrected based on the latest white dwarf spectral fitting models in Tremblay & Bergeron 2009).

2. A new application: the age of the Milky Way inner halo

White dwarf stars have long been used as chronometers to date stellar populations (e.g., Winget et al. 1987). With no nuclear fuel, white dwarfs simply cool as they age and the present-day luminosity can be used to infer the age. This age is a lower limit to the total age, since it does not include the progenitor lifetime of the star that made the white dwarf.

However, through the initial-final mass relation, white dwarfs can also be used to establish ages of stellar populations using a different technique. Kalirai (2012) develop this method by using the mass of *newly* forming white dwarfs in old stellar populations as a proxy for the turnoff mass. In their study, they first anchor a new relation on the globular cluster M4, where there is both a reliable age measurement from the main-sequence turnoff (Dotter et al. 2010; 12.5 ± 0.5 Gyr) and a reliable white dwarf mass measurement at the tip of the cooling sequence (Kalirai et al. 2009; 0.529 ± 0.012 $M_{\odot}$). Based on the Dotter et al. (2009) models, this snapshot of stellar evolution indicates that 0.80 $M_{\odot}$ metal-poor main-sequence stars evolve to form 0.529 ± 0.012 $M_{\odot}$ white dwarfs. Relative to this anchor, the present-day evolving main-sequence mass of metal-poor stars can now be calculated by simply measuring the remnant masses of newly formed white dwarfs in the same population. Kalirai (2012) select such white dwarfs in the local inner halo of the Milky Way. These stars were discovered by the SN Ia Progenitor Survey (SPY) in Pauli et al. (2006), through a full kinematic analysis. The remnant mass, based on the same white dwarf models used for the M4 white dwarfs, is 0.551 ± 0.005 $M_{\odot}$. These white dwarfs are heavier than the M4 white dwarfs, and therefore the evolving present day mass of the turnoff is higher, and the population is younger. As Figure 2 shows, the calculated age of the inner halo from these data is 11.4 ± 0.7 Gyr.

The new relation to derive a population's age from this method is provided in Figure 2. We caution that this approach only works for metal-poor stars that are old, and assumes that the small difference in remnant mass tracks the difference in turnoff mass at low masses of M_{initial} = 0.80 – 0.90 $M_{\odot}$. As the relation is anchored on the globular cluster M4, the zero point can change depending on any newly derived age of the cluster (we have used 12.5 Gyr from the Dotter et al. 2010 study). This would lead to a proportionally different age for the inner halo white dwarfs. As pointed out by R. Gratton at the, "Reading the Book of Globular Clusters with the Lens of Stellar Evolution" meeting, specific second order differences in the nature of the evolving stars in M4 versus the field will also affect this result (e.g., if the cluster stars are enhanced in helium, then the evolving mass is slightly different at fixed age).

3. Other applications of the initial-final mass relation, and future outlook

A full characterization of the initial-final mass relation has broad applications in astrophysics. Over the past few years, our relation has been used to infer properties of planetary nebulae (e.g., Ciardullo 2010), to characterize exoplanets hosts (e.g., Kilic, Gould, & Koester 2009), to measure supernovae rates, evolution, and progenitors (e.g., Pritchet, Howell, & Sullivan 2008; Greggio 2010; Kistler et al. 2011), to constrain star formation scenarios in galaxies (Leitner & Kravtsov 2011), to study disc galaxy formation in ΛCDM models (e.g., Agertz, Teyssier, & Moore 2010), to calculate the IMF of stars (e.g., Lockmann, Baumgardt, & Kroupa 2010), to produce population syn-

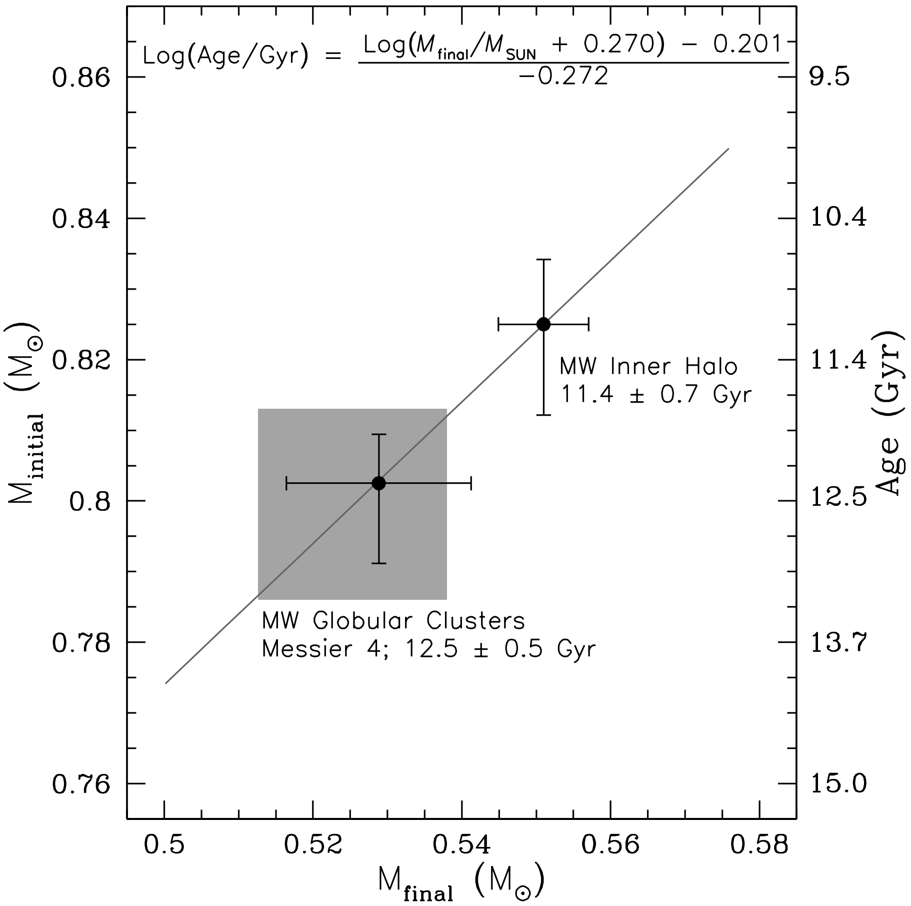

Fig. 2. White dwarf spectroscopy in the globular cluster M4 establishes the present-day formation mass of remnants to be $0.529 \pm 0.012\ M_{\odot}$. These stars are evolving from $0.80\ M_{\odot}$ progenitors, given the age of the cluster at 12.5 Gyr (Dotter et al. 2010). The age distribution of the Milky Way globular cluster population is marked by the shaded region. The newly formed white dwarfs in the Milky Way inner halo, as selected from the SPY survey (Pauli et al. 2006) are heavier than the M4 remnants, thereby indicating a present day turnoff mass that is larger. The age of the local inner halo is measured to be 11.4 ± 0.7 Gyr, as described in Kalirai (2012).

thesis models (e.g., Kotulla et al. 2009), and much more. Looking forward, it would be highly desirable to add two new dimensions to the initial-final mass relation. First, a more robust exploration of the upper mass limit to white dwarf formation is needed. Not only will this provide insights to models of massive degenerate objects, but the transition mass is also the lower mass limit to type II SNe formation. The transition mass is a central parameter to reliably predict feedback energetics in galaxies. Second, most of the star clusters studied thus far have Solar metallicity. Examination of the initial-final mass relation in clusters with non-Solar metallicity will yield important constraints on the variation of stellar mass loss with abundance.

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