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A new method to measure stellar mass-loss rates

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Abstract. The total stellar mass loss that a star suffers through post-main-sequence evolution is of vital importance to understand its subsequent evolution. The mass-loss rate along the first-ascent red-giant branch alone determines the upper red-giant-branch luminosity function and horizontal-branch morphology. The distribution of stars in these phases directly affects our interpretation of the integrated colors of distant galaxies, and is therefore of fundamental importance for galaxy formation and evolution studies in the higher-redshift Universe. Yet, these mass-loss rates, especially as a function of age and metallicity, are very poorly constrained in current models. I present new constraints on this field based on imaging and spectroscopic observations of the end products from this evolution, white dwarfs. By studying the mass distribution of these dead stars in nearby star clusters with a range of (known) ages and metallicities, we can directly constrain the mass-loss rates of stars across a range of environments. These observations directly impact several fields in astrophysics, including our knowledge of the enrichment of the interstellar medium, our ability to construct population synthesis models to interpret galaxy colors and the general interpretation of the sources and processes responsible for the observed ultraviolet upturn in elliptical galaxies.

Keywords. stars: mass loss, techniques: photometric, techniques: spectroscopic, white dwarfs

1. The importance of measuring stellar mass loss

Correctly characterizing the amount of mass loss that stars suffer through post-main-sequence evolution represents one of the most important and fundamental goals of stellar astrophysics. The mass-loss rate on the first-ascent red-giant branch alone can drastically affect the eventual fate of an evolving star. For example, the total integrated red-giant-branch mass loss can affect the location that a star leaves the red-giant branch for low-mass stars (e.g., Castellani & Castellani 1993; D'Cruz *et al.* 1996; Kalirai *et al.* 2007), and therefore alters the upper red-giant-branch luminosity function. Equally important, higher rates of mass loss lead to hotter exposed stars, which will occupy a bluer position on the subsequent core helium-burning horizontal branch (Rood 1973). Extremely high levels of mass loss on the red-giant branch can also lead to stars with very thin hydrogen envelopes that bypass both of these phases and evolve directly to the white-dwarf cooling sequence with helium cores (e.g., Hansen 2005; Kalirai *et al.* 2007), or those that experience late flashes (e.g., see D'Cruz *et al.* 1996). Clearly, the initial phases of mass loss after the main sequence can have widespread implications for the subsequent evolution of stars.

Unfortunately, theoretical predictions of post-main-sequence stellar mass loss are difficult to calculate because of our insufficient understanding of mass-loss mechanisms on the red-giant branch and at the helium flash, and also the unknown number of thermal pulses on the asymptotic giant branch (e.g., Habing 1996; Weidemann 2000). The mass-loss rates depend on the assumed composition of the dust grains, the dust-to-gas ratio, the expansion velocity of the stellar envelope and the temperature/luminosity of the star (e.g., Groenewegen 2006). Given our lack of knowledge of these basic stellar properties, variations in mass-loss recipes are large, leading to large uncertainties in our basic predictions from stellar evolution models and therefore our interpretation of the properties of stars in these phases today (see, e.g., Catelan 2007). We note that the different models especially disagree with one another at metallicities above solar.

A combination of photometric and spectroscopic efforts have recently led to the construction of an initial–final mass relation over a wide mass range. The relation simply illustrates the connection between the final remnant white-dwarf mass, and its initial progenitor mass, and therefore directly probes stellar mass loss. Kalirai *et al.* (2008) present the first results on the low-mass end of the relation, by undertaking a new spectroscopic campaign targeting white dwarfs in old open star clusters. Kalirai *et al.* (2007) and Kalirai *et al.* (2009) also extend the relation to both a single metal-rich and metal-poor cluster, and therefore a preliminary estimate of the dependences of mass loss on metallicity can be calculated. Given that the white dwarfs are end products of both the red-giant and asymptotic giant-branch phases, we cannot strictly use our observations to constrain the red-giant-branch mass loss, but rather the total integrated mass loss through all of the post-main-sequence evolutionary phases.

2. The data

A large number of observations over the past 30 years have successfully established the initial–final mass relation for solar metallicity and $M_{\rm initial} \gtrsim 3$ M$_\odot$ (a complete summary is provided in Kalirai *et al.* 2009). The first step in this process involves imaging rich star clusters down to sufficient depth to yield white-dwarf candidates (e.g., the *CFHT* Open Cluster Survey: Kalirai *et al.* 2001a,b,c, 2003). These stars are then followed with spectroscopy to (i) verify their white-dwarf nature and (ii) build up enough signal-to-noise ratio to accurately characterize the higher-order Balmer lines (e.g., Hϵ and H8). Recently, the bulk of these observations have been carried out using the *Keck*/LRIS multiobject spectrograph on Mauna Kea (e.g., Williams, et al. 2004, 2009; Williams & Bolte 2007; Kalirai *et al.* 2005, 2007, 2008, 2009). Multiobject capabilities essentially allow sampling of fainter white dwarfs since their spectra are simultaneously obtained on the same spectroscopic mask, in the same exposures (e.g., 20–30 white-dwarf candidates are observed together). As mentioned above, the more recent observations of the initial–final mass relation presented in Kalirai *et al.* (2008) provide the first mass measurements of white dwarfs in old open clusters.

The white-dwarf spectra are analyzed with atmosphere models to yield the fundamental properties of each star, e.g., temperature and gravity (Bergeron *et al.* 1992, 1995). With these in hand, the radius (and therefore mass) of the star can be easily calculated. As the stars belong to a star cluster, the main-sequence turnoff mass of their parent cluster is also known, and a small correction can be applied to yield the progenitor mass of each of the white dwarfs (e.g., the main-sequence lifetime of the progenitor is simply the difference between the cluster age and the white-dwarf cooling age of each individual star).

3. Characterizing stellar mass loss from white-dwarf spectroscopy

3.1. *The solar-metallicity initial–final mass relation*

The most recent initial–final mass relation, calculated using the entire set of observations up to 2009, is presented in Kalirai *et al.* (2008). This relation requires a small correction to reflect the new Stark broadening calculations presented in Tremblay & Bergeron (2009),

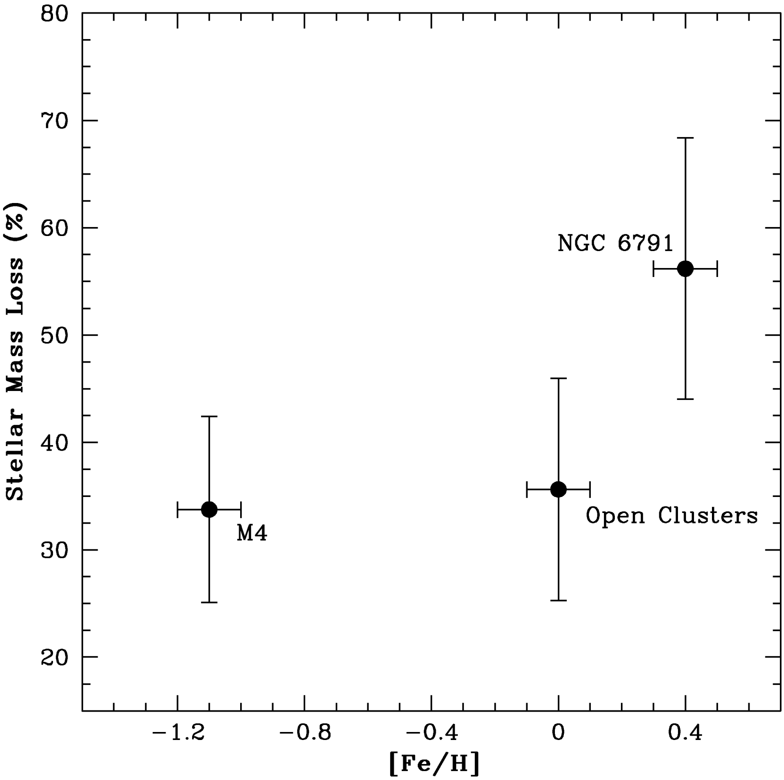

Figure 1. The total integrated mass loss through post-main-sequence evolution is shown for three different regimes, all measured by comparing the mass distribution of white dwarfs in star clusters to their progenitor mass. For both a single metal-poor globular cluster and for many rich open clusters, the mass loss is measured to be ∼35%. At supersolar metallicities, our spectroscopic measurements of the mass of NGC 6791's white dwarfs suggest high levels of mass loss.

which results in a shift in all spectroscopic white-dwarf mass measurements of $+0.03\ M_\odot$. The general form of the relation is such that more massive progenitor stars produce more massive white dwarfs. The data are well fit by a simple linear relation, $M_{\rm final} = (0.109 \pm 0.007)\ M_{\rm initial} + (0.428 \pm 0.025)\ M_\odot$. We can therefore estimate that solar-metallicity stars with $M_{\rm initial} = 0.80 \pm 0.05\ M_\odot$ will form white dwarfs with $M_{\rm final} = 0.52 \pm 0.03\ M_\odot$. These stars will therefore lose 35% of their mass through post-main-sequence stellar evolution, as shown in Figure 1.

3.2. *Mass loss in metal-poor and metal-rich stars*

Kalirai *et al.* (2009) provided the first data point on the initial–final mass relation that comes from a population II system. Their *Keck*/LRIS spectroscopic study of white dwarfs in M4, [Fe/H] = −1.1 (Marino *et al.* 2008), indicates that 0.8 $M_\odot$ progenitors form 0.53 $M_\odot$ white dwarfs, an integrated mass loss of 34%. This therefore indicates that the evolution of low-mass stars that are chemically anemic leads to white dwarfs with approximately the same mass as in the solar-metallicity case. So, the mass-loss/metallicity relation may, in fact, be relatively flat between these metallicity regimes.

Unlike the findings above, Kalirai *et al.* (2007) found evidence for enhanced mass loss at extremely high metallicities. By studying the white-dwarf mass distribution in the supersolar-metallicity star cluster NGC 6791 ([Fe/H] = +0.40; Origlia *et al.* 2006;

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Gratton *et al.* 2006), they showed that not only is the mass loss stochastic, but can also approach values as high as 55–60%. Formally, correcting for the +0.03 $M_\odot$ offset in Tremblay & Bergeron (2009), Kalirai *et al.* (2007) measure the mean white-dwarf mass to be $M_{\rm final} = 0.46 \pm 0.06$ $M_\odot$ (the cluster main-sequence turnoff mass is $\sim$1.05 $M_\odot$). As they discuss, such evolution likely leads to the formation of helium-core white dwarfs in this cluster.

Data points for these two regimes are also shown in Figure 1 and suggest that the form of the mass-loss/metallicity relation is not linear over a large range in metallicity. As Catelan (2007) show, some theoretical relations predict an almost exponential-type behavior of mass loss as a function of metallicity at very high metallicities [e.g., the Goldberg (1979) and Judge & Stencel (1991) relations]. Our preliminary results from this analysis, from the study of just one metal-rich and one metal-poor cluster, are qualitatively similar to such relations.

4. Summary and implications

The relationship between stellar mass loss and metallicity is fundamentally important to understand the evolution of stars beyond the main sequence. Characterizing the amount of mass loss that stars suffer, as a function of their initial mass and metallicity (as well as rotation, magnetism and other properties), leads to the eventual distribution of stars along post-main-sequence evolutionary phases such as the horizontal and asymptotic giant branches. Unlike nearby stellar systems such as Galactic star clusters, we have no direct means to separate the unresolved light that we measure from distant galaxies into these evolutionary sequences. Yet, given the brightness of stars in these phases of stellar evolution, the ultraviolet and blue light is dominated by hot horizontal-branch stars and the red light by asymptotic and red-giant-branch stars.

An excellent example of the influence of stellar evolution in shaping an unexpected spectral response can be seen in most elliptical galaxies. Despite these systems being old, metal-rich galaxies, the spectral-energy distribution for many ellipticals shows a rise in ultraviolet light (Burstein *et al.* 2008; Bressan *et al.* 1994; O'Connell 1999). In the absence of star formation and hot, young stars, the most natural source that can emit appreciably in the ultraviolet is an extremely hot horizontal-branch star (Greggio & Renzini 1990). The formation of such stars almost certainly results from enhanced mass loss along the red-giant branch, either from binary evolution or from wind-driven mass loss (Han *et al.* 2007; Kalirai *et al.* 2007). In its basic properties, the open star cluster NGC 6791 is similar to an elliptical galaxy; it is an old, metal-rich system. To explain the ultraviolet excess, Dorman, O'Connell, & Rood (1995) estimate that 15–20% of a population's evolving stars would need to populate the extremely blue horizontal branch, which is much lower than the fraction of stars actually seen in this phase in the [Fe/H] = +0.4 cluster NGC 6791.

Recently, the metallicity distribution function (MDF) of the Galactic bulge has been probed with dwarfs for the first time. Given the need for high-resolution, high signal-to-noise spectra, previous studies have been forced to measure the MDF with red giants (e.g., Zoccali *et al.* 2003). The new dwarf measurements result from stars that are microlensed, and therefore have amplified fluxes. With quick spectroscopic follow up, Cohen *et al.* (2008, 2009) and Johnson *et al.* (2008) showed that the few dwarfs in the Galactic bulge with accurate metallicity measurements are extremely metal-rich and inconsistent with the MDF from red giants. A possible explanation for this disparity may be related to biases in the giant MDF, for example, if the metal-rich dwarfs 'peel' away from the red-giant branch prior to reaching the tip, given enhanced mass loss (e.g., Castellani

& Castellani 1993). As the present sample only includes half a dozen dwarfs, it will be important to target more microlensed stars and build upon the statistics in this comparison.†

As Kilic *et al.* (2007) demonstrate, production of low-mass white dwarfs through enhanced mass loss appears to be a general occurrence in our Galaxy. In addition to the studies above, such a relation between mass loss and metallicity may also impact our understanding of planetary systems around white dwarfs and the varying characteristics of supernovae in spiral versus elliptical galaxies. More concrete conclusions will require verifying the hints that we have thus far seen by probing white-dwarf properties in systems spanning a wide range in metallicity. Fortunately, many more star clusters can be subjected to these types of studies with current 8–10m-class telescopes, as well as with the next-generation 30 m telescopes.

References

Bensby, T., *et al.* 2009, *IAU Symp.* No. 265, in press (arXiv:0908.2779)
Bergeron, P., Saffer, R. A., & Liebert, J. 1992, *ApJ*, 394, 228
Bergeron, P., Liebert, J., & Fulbright, M. S. 1995, *AJ*, 444, 810
Bressan, A., Chiosi, C., & Fagotto, F. 1994, *ApJS*, 94 63
Burstein, D., Bertola, F., Buson, L. M., Faber, S. M., & Lauer, T. R. 1988, *ApJ*, 328, 440
Castellani, M. & Castellani, V. 1993, *ApJ*, 407, 649
Catelan, M. 2007, in: M. Chavez, E. Bertone, D. Rosa-Gonzalez, and L. H. Rodríguez–Merino (eds.), *New Quests in Stellar Astrophysics II: The Ultraviolet Properties of Evolved Stellar Populations*, p. 175, Springer
Cohen, J. G., Huang, W., Udalski, A., Gould, A., & Johnson, J. A. 2008, *ApJ*, 682, 1029
Cohen, J. G., Thompson, I. B., Sumi, T., Bond, I., Gould, A., Johnson, J. A., Huang, W., & Burley, G. 2009, *ApJ*, 699, 66
D'Cruz, N. L., Dorman, B., Rood, R. T., & O'Connell, R. W. 1996, *ApJ*, 466, 359
Dorman, B., O'Connell, R. W, & Rood, R. T. 1995, *ApJ*, 442, 105
Goldberg, L. 1979, *QJRAS*, 20, 361
Gratton, R., Bragaglia, A., Carretta, E., & Tosi, M. 2006, *ApJ*, 642, 462
Greggio, L. & Renzini, A. 1990, *ApJ*, 364, 35
Groenewegen, M. A. T. 2006, *A&A*, 448, 181
Habing, H. J. 1996, *ARA&A*, 7, 97
Han, Z., Podsiadlowski, P., & Lynas–Gray, A. E. 2007, *MNRAS*, 380, 1098
Hansen, B. M. S. 2005, *ApJ*, 635, 522
Johnson, J. A., Gaudi, B. S., Sumi, T., Bond, I. A., & Gould, A. 2008, *ApJ*, 685, 508
Judge, P. G. & Stencel, R. E. *1991*, ApJ, 371, 357
Kalirai, J. S., Richer, H. B., Fahlman, G. G., Cuillandre, J., Ventura, P., D'Antona, F., Bertin, E., Marconi, G. & Durrell, P. 2001a, *AJ*, 122, 257
Kalirai, J. S., Richer, H. B., Fahlman, G. G., Cuillandre, J., Ventura, P., D'Antona, F., Bertin, E., Marconi, G., & Durrell, P. 2001b, *AJ*, 122, 266
Kalirai, J. S., Ventura, P., Richer, H. B., Fahlman, G. G., D'Antona, F. & Marconi, G. 2001c, *AJ*, 122, 3239
Kalirai, J. S., Fahlman, G. G., Richer, H. B., & Ventura, P. 2003, *AJ*, 126, 1402
Kalirai, J. S., Richer, H. B., Reitzel, D., Hansen, B. M. S., Rich, R. M., Fahlman, G. G., Gibson, B. K., & von Hippel, T. 2005, *ApJ* (Letters), 618, L123
Kalirai, J. S., Bergeron, P., Hansen, B. M. S., Kelson, D. D., Reitzel, D. B., Rich, R. M., & Richer, H. B. 2007, *ApJ*, 671, 748
Kalirai, J. S., Hansen, B. M. S., Kelson, D. D., Reitzel, D. B., Rich, R. M., & Richer, H. B. 2008, *ApJ*, 676, 594

† A recent preprint by Bensby *et al.* (2009) shows that the disparity in the MDF between the dwarfs and giants is significantly reduced based on a larger set of observations.

Kalirai, J. S., Davis, D. S., Richer, H. B., Bergeron, P., Catelan, M., Hansen, B. M. S., & Rich, R. M. 2009, *ApJ*, 705, 408
Kilic, M., Stanek, K. Z., & Pinsonneault, M. H. 2007, *ApJ*, 671, 761
Marino, A. F., Villanova, S., Piotto, G., Milone, A. P., Momany, Y., Bedin, L. R., & Medling, A. M. 2008, *A&A*, 490, 625
O'Connell, R. W. 1999, *ARA&A*, 37, 603
Origlia, L., Valenti, E., Rich, R. M., & Ferraro, F. R. 2006, *ApJ*, 646, 499
Rood, R. T. 1973, *ApJ*, 184, 815
Tremblay, P.-E. & Bergeron, P. 2009, *ApJ*, 696, 1755
Weidemann, V. 2000, *A&A*, 363, 647
Williams, K. A., Bolte, M., & Koester, D. 2004, *ApJ* (Letters), 615, L49
Williams, K. A & Bolte, M. 2007, *AJ*, 133, 1490
Williams, K. A., Bolte, M., & Koester, D. 2009, *ApJ*, 693, 355
Zoccali, M., *et al.* 2003, *A&A*, 399, 931