Observational Constraints on the Age-Metallicity Relation from White Dwarf-Main Sequence Binaries


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Abstract. The age-metallicity relation (AMR) is a fundamental observational property to understand how the Galactic disc formed and evolved chemically in time. However, there is not yet a consensus on the observed properties of the AMR for the solar neighbourhood. This is due primarily to the difficulty of obtaining precise stellar ages for individual field stars. We have started an observational campaign to provide the much needed observational AMR by using white dwarf-main sequence (WDMS) binaries. White dwarfs are natural clocks and can be used to derive accurate ages. Metallicities can be obtained from the main sequence companions. Since white dwarfs and main sequence stars in these binary systems are coeval, these binaries provide an unique opportunity to observationally determine in a robust way the AMR. Here we present the AMR derived from the analysis of a sample of 23 WDMS binaries.

1. Introduction

The observed evolution of stellar abundances as a function of age – that is, the age-metallicity relation (AMR) – is the fossil record of the chemical evolution and enrichment history of the Galactic disc. The AMR is thus a fundamental observational property to understand how the Galactic disc formed, and how it evolved chemically. The AMR has been extensively studied over the years – see, for instance, the reviews of Freeman & Bland-Hawthorn (2002) and Nomoto et al. (2013). While early observational studies found a correlation between stellar ages and metallicity in the solar
vicinity (Rocha-Pinto et al. 2000; Soubiran et al. 2008), more recent studies show a substantial scatter in the relation, suggesting that a clear correlation between the age and the metallicity does not exist (Haywood et al. 2013; Bergemann et al. 2014). These differences in the observed AMRs are likely to arise because measuring precise stellar ages is a difficult task, prone to substantial uncertainties (Soderblom 2010). Indeed, substantial differences between different works arise when comparing ages derived for the same stars (Anguiano et al. 2010). The discrepancies in stellar ages, and hence in the derived AMRs, motivate to explore other dating methods.

White dwarf-main sequence (WDMS) binary systems are detached pairs composed of a white dwarf (WD) and a main sequence (MS) star. They evolve from MS binaries through two different channels (Willems & Kolb 2004). In ~75% of the cases, the initial separation is wide enough to allow stars to evolve as if they were single, avoiding mass transfer episodes. In the remaining ~25% of the cases the stars are close enough so that the binaries undergo a phase of mass transfer, known as the common envelope phase (Webbink 2008). Dissipation inside the common envelope results in a rapid decrease of the binary separation. Henceforth, orbital energy and angular momentum are extracted from the binary orbit, leading to the ejection of the envelope. This results in a WDMS binary in a close orbit. As a consequence the orbital period distribution of WDMS binaries is bi-modal. One of the peaks corresponds to systems that passed through the common envelope phase, and is located at short orbital periods, whereas systems that evolved avoiding any mass transfer episode form a secondary peak at long orbital periods.

Here we present the results of an observational campaign aimed at measuring the AMR by employing WDMS binaries. Using WDMS binaries has significant advantages over other methods because WDs are objects with well-studied properties that can be used to derive accurate ages. Moreover, metallicities can be directly determined for the MS companions in the same way as for individual field stars. Since the two stars in the binary are coeval, employing accurate WD ages also allows to determine the age of their MS companions.

2. The WDMS Binary Sample

Our catalog of WDMS pairs is the largest and most homogeneous one (Rebassa-Mansergas et al. 2016). It has been obtained from the Sloan Digital Sky Survey (SDSS). Radial velocity determinations have allowed the identification of hundreds of both close SDSS WDMS binaries that evolved through a common envelope phase, and wide binaries that did not interact (Rebassa-Mansergas et al. 2007, 2011). Close WDMS binaries cannot be employed in our study, since the evolution of the WD progenitors was truncated during the common envelope phase, and consequently they do not have a well defined initial-to-final mass relation. Among the sub-population of wide SDSS WDMS binaries, we selected 118 systems which are bright enough ($g < 19$ mag) to allow obtaining accurate WD ages and MS star metallicities from spectroscopic observations employing medium- and large-aperture ground based telescopes.
Figure 1. Example X-Shooter spectrum of SDSSJ0036+0700, an SDSS WDMS binary in our sample (black; regions dominated by telluric absorption are shown in gray). The WD dominates the flux contribution at blue wavelengths ($\lambda < 600$ nm), the MS companion contributes most to the red (and near-infrared) part of the spectrum. The best-fit WD model and MS star template to the observed optical spectrum are shown as blue and red solid lines. On the top right corner we zoom-in to the Na\textsc{i} absorption doublet at 2205/2209 nm, used to derive the MS star [Fe/H] abundance. Right panel: the normalised residual WD Balmer lines (black) that result from subtracting the MS star contribution and the best-fit WD model (blue).

3. Observations

We observed 19 wide WDMS binaries in our sample with the Very Large Telescope at Cerro Paranal (Chile) equipped with the X-Shooter instrument. X-Shooter takes simultaneous spectra on three different arms (UVB; 3,000–5,600 Å, VIS; 5,500–10,200 Å, NIR; 10,200–24,800 Å) thus covering the 3,000–24,800 Å wavelength range in one single exposure. The data were reduced, wavelength calibrated and flux calibrated with the ESOREFLEX X-Shooter pipeline, version 2.6.8. An example of reduced and calibrated spectrum is shown in the left panel of Fig. 1. Three additional wide SDSS WDMS binaries in our sample were previously observed by X-Shooter by some of us in a separate programme, aimed at measuring accurate temperatures for ZZ Ceti WDs in detached WDMS binaries (Pyrzas et al. 2015): SDSSJ0052-0051, SDSSJ0824+1723 and SDSSJ0111+0009. We reduced these data in the same way as described above. Finally, we included in our sample the eclipsing SDSS WDMS binary SDSSJ0138-0016 (Parsons et al. 2012), which has also been observed intensively with the X-Shooter instrument. With an orbital period of 1.7 hours, this system has evolved through a common envelope phase. However, it contains an ultra-cool WD (3570 K) that allows to derive a robust cooling age of 9.5 Gyr. We reduced and calibrated the NIR X-Shooter data of SDSSJ0138-0016 to derive the metallicity of the MS companion.

4. Results

In total we have X-Shooter spectra of 23 wide WDMS binaries. Here we report the spectral analysis performed to derive the WD ages and MS star metallicities together with the AMR derived from this pilot sample.
4.1. WD Ages

We used the decomposition/fitting routine outlined by Rebassa-Mansergas et al. (2007) to subtract the MS star contribution from the combined UVB and VIS arm X-Shooter spectra and record the MS star spectral type. We then fitted the normalised Balmer lines of the residual WD spectra (see an example in Fig. 1, right panel) with the model grid of Koester (2010) considering the 3D corrections by Tremblay et al. (2013), and derived WD effective temperatures and surface gravities. Afterwards, we interpolated these values using the cooling tracks of Renedo et al. (2010) to obtain the WD masses and cooling ages. We then used the initial-to-final mass relation of Catalán et al. (2008) to derive the WD progenitor masses. Finally, the WD progenitor lifetimes were obtained interpolating the WD progenitor masses in the BASTI isochrones (Pietrinferni et al. 2004), for which we adopted the metallicities derived from the MS companions, see below. The WD cooling ages added to the MS lifetimes of their progenitors gave the total ages of the binaries.

4.2. MS Star Metallicities

Due to selection effects, the SDSS WDMS binary sample is biased towards the detection of low-mass MS companions of spectral type M (Rebassa-Mansergas et al. 2010). Several methods exist for measuring M dwarf metallicities (specifically [Fe/H] abundances) from low/medium resolution infrared spectra such as those obtained in this work (Rojas-Ayala et al. 2012; Mann et al. 2014; Newton et al. 2014). The methods described by Rojas-Ayala et al. (2012) and Mann et al. (2014) make use of semi-empirical relations based on the equivalent widths of different atomic lines (Ca I and Na I) as well as the H_20-K2 index to obtain [Fe/H]. However, deriving the H_20-K2 index requires measuring the median flux in the 2,360–2,480 nm range, which is unfortunately dominated by noise in our spectra. Thus, we obtained the [Fe/H] abundances from the K-band, NIR X-Shooter spectra of the M dwarfs (see Fig. 1) following the procedure described in Newton et al. (2014). This method provides [Fe/H] following a semi-empirical multivariate linear regression based solely on the Na I absorption doublet (2,205/2,209 nm) equivalent width.

In the upper panel of Fig. 2 we display our resulting AMR. In the bottom panel of the same figure we display the average ⟨[Fe/H]⟩ per 1 Gyr bins along with their standard deviations (σ) adopting three different initial-to-final mass relations. The AMR derived in this way shows an intrinsic scatter >0.2 dex for most ages, independently of the assumed initial-to-final mass relation. This significant scatter suggests a lack of correlation between the values of [Fe/H] and ages derived from our pilot data-set of 23 WDMS systems.

5. Conclusions

For young and intermediate ages (≤8 Gyr), we find that the averaged AMR fluctuates between −0.4 to +0.3 dex, but does not show any apparent slope. Although more data are needed to draw more solid conclusions about the slope of the AMR in this region, our observations agree with similar studies (Casagrande et al. 2011; Haywood et al. 2013; Bergemann et al. 2014) using sub-giants and turnoff stars. Also, Casagrande et al. (2011), Haywood et al. (2013), and Bergemann et al. (2014) found a decline of [Fe/H] for ages longer than ~8 Gyr. However, our current data do not allow us to
Figure 2. The age-[Fe/H] relation derived from the 23 SDSS WDMS binaries studied in this work. The ages are obtained assuming the initial-to-final mass relation of Catalán et al. (2008). Bottom panel: average [Fe/H] values for 1 Gyr bins, together with their standard deviations ($\sigma$) for ages derived using the initial-to-final mass relation of Catalán et al. (2008) – black dots – Ferrario et al. (2005) – cyan squares – and Gesicki et al. (2014) – red triangles. The observed scatter of [Fe/H] at all ages remains, independently of the adopted initial-to-final mass relationship.

confirm this trend of the AMR. Finally, we find an intrinsic scatter of $\sim 0.2$ dex in our AMR, a value larger than the nominal observational error on $[\text{Fe/H}]$ (0.12 dex). The fact that we observe a large scatter of $[\text{Fe/H}]$ for young and intermediate ages, as previously reported in several other observational studies targeting field stars, supports the idea of the methods used for calculating stellar ages (e.g. chromospheric activity, isochrone fitting) being reliable. However, it is noteworthy that differences arise when comparing individual ages of selected field stars derived using different techniques (Anguiano et al. 2010). This makes it difficult to assess which of the employed methods is more reliable.

Our results provide clear additional observational evidence for the existence of a physical mechanism that is at the origin of the observed scatter of $[\text{Fe/H}]$ in the observed AMR in the solar neighbourhood. Several mechanisms have been suggested to explain the scatter observed in the AMR. Among them, the currently most accepted scenario invokes radial migration effects – metal-rich stars form in the inner disc and subsequently migrate to the metal-poorer outer disc (Roškar et al. 2008; Minchev et al. 2011). Due to the small WDMS binary sample size we cannot yet confirm nor discard
any of these (or any other) scenarios. Clearly, the analysis of a larger sample will help in settling all these issues.

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References

Anguiano, B., Freeman, K. C., Steinmetz, M., & de Boer, E. W. 2010, Galaxies and their Masks, 313