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MAGNESIUM ISOTOPES IN METAL-POOR DWARFS: THE RISE OF AGB STARS AND THE FORMATION TIMESCALE OF THE GALACTIC HALO[1]

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ABSTRACT

We have determined magnesium isotopic ratios (^{25,26}Mg/Mg) in metal-poor ($-2.6 \leq$ [Fe/H] ≤ -1.3) halo dwarfs employing high signal-to-noise ratio (S/N = 90–280), high spectral resolution ($R = 10^5$) Keck High Resolution Echelle Spectrometer (HIRES) spectra. Unlike previous claims of an important contribution from intermediate-mass asymptotic giant branch (AGB) stars at low metallicities, we find that the rise of the AGB contribution in the Galactic halo did not occur until intermediate metallicities ([Fe/H] $\gtrsim -1.5$).

Subject headings: Galaxy: halo — stars: abundances — stars: AGB and post-AGB — stars: atmospheres — stars: Population II

1. INTRODUCTION

Magnesium is composed of three stable isotopes, ^{24}Mg, ^{25}Mg, and ^{26}Mg, that can be formed in massive stars (e.g., Woosley & Weaver 1995, hereafter WW1995). The lightest isotope is formed as a primary isotope from H, while ^{25,26}Mg are formed as secondary isotopes. The heaviest Mg isotopes are also produced in intermediate-mass AGB stars (Karakas & Lattanzio 2003), so the isotopic ratios ^{25,26}Mg/^{24}Mg increase with the onset of AGB stars. Therefore, Mg isotopic ratios in halo stars could be used to constrain the rise of AGB stars in our Galaxy.

It is important to know when AGB stars begin to enrich the halo in order to disentangle the contribution of elements produced by intermediate-mass stars from the contribution of elements produced by massive stars. For example, the high nitrogen abundances observed in metal-poor stars can be explained by fast-rotating massive stars (Chiappini et al. 2005, 2006) or, alternatively, by intermediate-mass stars, although the latter option may be unlikely because those stars may not have had time to enrich the halo due to their longer lifetime.

Mg isotopic abundances can be obtained from the analysis of MgH lines in cool stars. After the early work of Boesgaard (1968) and Bell & Branch (1970), other studies have increased the coverage in metallicity down to [Fe/H] $= -1.8$ (Tomkin & Lambert 1980; Lambert & McWilliam 1986; Barbuy 1985, 1987; Barbuy et al. 1987; McWilliam & Lambert 1988; Gay & Lambert 2000).

In order to reach lower metallicities ([Fe/H] < -2), very metal-poor cool dwarfs have to be discovered. This work was undertaken by Yong & Lambert (2003a, 2003b), who found a number of metal-poor ([Fe/H] < -2) cool dwarfs ($T_{\rm eff} <$ 5000 K) useful for Mg isotopic studies. Employing that sample, Yong et al. (2003, hereafter YLI2003) were able to study ^{25,26}Mg/^{24}Mg ratios down to [Fe/H] $= -2.5$. Surprisingly, they found metal-poor stars with relatively high ^{25,26}Mg/^{24}Mg ratios, thus suggesting an important contribution by intermediate-mass AGB stars even at such low metallicities (Fenner et al. 2003, hereafter F2003).

In this work, we determine Mg isotopic ratios in cool halo dwarfs and constrain the rise of intermediate-mass AGB stars by comparing the observed ratios with chemical evolution models.

2. SAMPLE STARS AND OBSERVATIONS

The sample was selected from previous spectroscopic analyses of metal-poor cool dwarfs (Yong & Lambert 2003a, 2003b). Five metal-poor stars were chosen covering the range $-2.6 \leq$ [Fe/H] ≤ -1.3: G69-18 (LHS 1138), G83-46 (LHS 1718), G103-50, G63-40 (LHS 2765), and the well-known, moderately metal-poor dwarf HD 103095, with [Fe/H] $=$ -2.6, -2.6, -2.2, -1.9, and -1.3, respectively.

The observations were obtained with HIRES (Vogt et al. 1994) at the Keck I telescope. The first set of spectra was taken in 2004 August, just a few days after a HIRES upgrade, thus taking advantage of improvements in efficiency, spectral coverage, and spectral resolution. A resolving power of $R \approx 10^5$ was achieved using a 0.4″-wide slit. Additional observations were obtained in 2004 November and 2005 June.

The spectral orders were extracted with MAKEE,[2] and IRAF was used for further data reductions (Doppler correction, continuum normalization, and combining spectra).

Two sample stars (G83-46 and G103-50) turned out to be double-lined stars, with G103-50 being a spectroscopic binary (Latham et al. 1988). These two stars were discarded from the analysis.

3. ATOMIC AND MOLECULAR DATA

Three wavelength regions at 5134.6, 5138.7, and 5140.2 Å are usually employed to determine the isotopic abundance ratios of ^{25,26}Mg to ^{24}Mg (e.g., McWilliam & Lambert 1988; YLI2003). For these regions, we adopted laboratory Fourier transform spec-

[1] The data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration.

[2] MAKEE was developed by T. A. Barlow specifically for reduction of Keck HIRES data. It is freely available at http://www2.keck.hawaii.edu/inst/hires/data_reduction.html.

TABLE 1
Atmospheric Parameters and Mg Isotopic Ratios

ID	E_{B-V} (mag)	$T_{\rm eff}$ (K)	log g (dex)	[Fe/H] (dex)	$v_{\rm mic}$ (km s^{-1})	$v_{\rm mac}$ (km s^{-1})	χ^2 Fit ^{25}Mg	χ^2 Fit ^{26}Mg	Eye Fit ^{25}Mg	Eye Fit ^{26}Mg
HD 103095 ……	0.000	5010	4.60	−1.35	0.5	3.0	2.4 ± 1.3	2.8 ± 1.6	3.5 ± 1.5	3.3 ± 1.5
G63-40 ……….	0.005	4686	4.81	−1.86	0.3	2.0	0.5 ± 2.2	1.2 ± 1.4	…	1.0 ± 2.0
G69-18 ……….	0.030	4480	4.75	−2.60	0.3	1.5	0.9 ± 2.0	1.5 ± 2.2	…	1.0 ± 2.0

Note.—Mg isotopic ratios are given with respect to ^{24}Mg + ^{25}Mg + ^{26}Mg and are expressed as percentages.

troscope measurements of the isotopic ^{24,25,26}MgH lines obtained by Bernath et al. (1985).

In addition, outside the recommended regions, laboratory wavenumbers for ^{24}MgH were taken from Bernath et al. (1985), and the corresponding ^{25,26}MgH line positions were computed by adding the theoretical isotopic shifts to the laboratory ^{24}MgH wavenumbers. The ^{25,26}MgH isotopic shifts were calculated using the relative reduced mass of ^{25,26}MgH to ^{24}MgH.

The energy levels were calculated using molecular constants by Shayesteh et al. (2004), and we adopted a dissociation energy of 1.27 eV (Balfour & Lindgren 1978). Oscillator strengths were obtained from transition probabilities given by Weck et al. (2003).

Molecular C_2 lines are also present in the same region, so a line list of C_2 lines was also implemented. Laboratory wavenumbers were taken from Amiot (1983) and Prasad & Bernath (1994). The rotational strengths (Hönl-London factors) were computed following Kovacs (1961), and we adopted an oscillator band strength of $f_{00} = 0.03$ (see Grevesse et al. 1991). Excitation potentials were computed using the molecular constants of Prasad & Bernath (1994), and a dissociation energy of 6.297 eV (Urdahl et al. 1991) was adopted.

Atomic lines present in the region were also included. The initial line list was based in the work of Barbuy (1985), and lines were added or discarded based on spectral synthesis of both the Sun and Arcturus spectra.

In previous works, the macroturbulence has been determined mainly using two lines: Ni I λ5115.4 and Ti I λ5145.5 (e.g., McWilliam & Lambert 1988; YLI2003). For the two more metal-poor stars in our sample, these lines became too weak, so we additionally used lines of Fe I and Ca I present in the 5569–5601 Å region.

For the atomic lines, we adopted transition probabilities from the NIST database[3]; astrophysical *gf*-values were derived when no entry was available.

[3] See http://physics.nist.gov/PhysRefData/ASD/

4. SPECTRAL SYNTHESIS ANALYSIS

The stellar parameters ($T_{\rm eff}$, log g, [Fe/H], v_t) were initially adopted from Meléndez & Barbuy (2002) for HD 103095 and from Yong & Lambert (2003b) for the other two stars. A check of the stellar parameters was done employing the infrared flux method $T_{\rm eff}$ calibrations of Ramírez & Meléndez (2005), *Hipparcos* parallaxes, Y^2 isochrones (Demarque et al. 2004), and our HIRES spectra. $E(B-V)$ was estimated using both interstellar Na I D lines and reddening maps (§ 4.1 of Meléndez et al. 2006). Reasonable agreement was found with respect to the stellar parameters given in the above references. Our final adopted values are given in Table 1.

Once the stellar parameters were set, the macroturbulence was determined by employing the Ni I λ5115.4 and Ti I λ5145.5 lines, as well as Fe I and Ca I lines around 5569–5601 Å.

The contribution of C_2 lines was constrained by spectral synthesis of the weak feature around 5135.7 Å, which is a blend of C_2 lines (5135.57 and 5135.69 Å) sometimes blended with an unidentified line on the red side (Gay & Lambert 2000). Fortunately, the observations are of such high resolution that it is possible to constrain the contribution of C_2 by employing the blue side of this feature, thus imposing an upper limit to blends by C_2 lines.

The Mg isotopic ratios were determined using spectral synthesis. After the first trials, it was clear that the ^{25,26}Mg isotopic ratios were lower than 5%, i.e., much lower than the terrestrial ratios (79 : 10 : 11). The computed synthetic spectra have isotopic ratios ranging from ^{24}Mg : ^{25}Mg : ^{26}Mg = 100 : 0 : 0 to 90 : 5 : 5.

Initially, the Mg isotopic ratios were determined by a fit (by eye) of the synthetic spectra to the HIRES-observed data of the three recommended regions (see § 3). The results are shown in Table 1. After the fits by eye were completed, we performed a χ^2 fit by computing $\chi^2 = \Sigma(O_i - S_i)/\sigma^2$, where O_i and S_i represent the observed and synthetic spectrum, respectively, and $\sigma = ({\rm S/N})^{-1}$. As an example of the χ^2 fits, we show in Figure 1 the fits for the recommended region at 5140.2 Å in

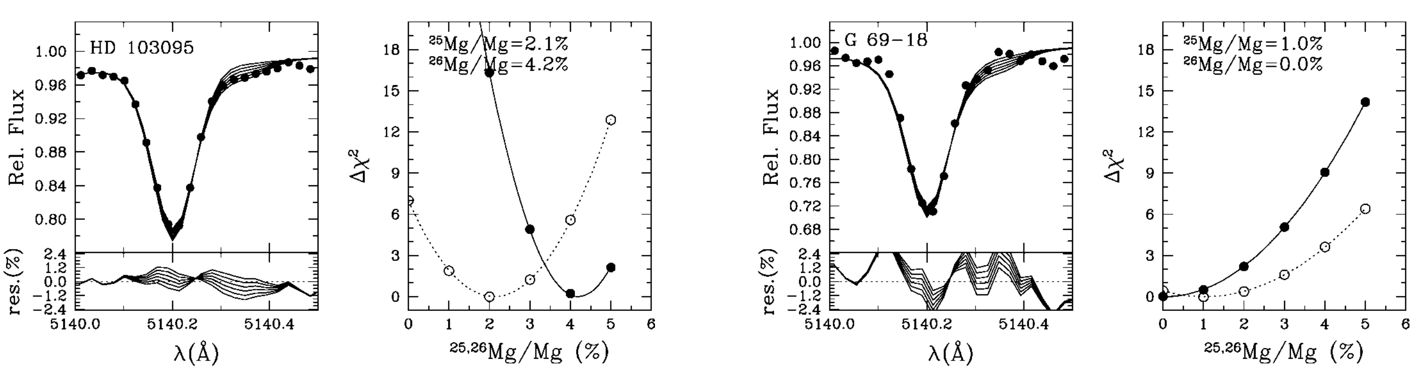

Fig. 1.—Fits for the 5140.2 Å region in the stars HD 103095 and G69-18. Observed spectra are represented as filled circles, and synthetic spectra as solid lines. The calculations were performed for ^{25,26}Mg/Mg ratios of 0–5%. The relative variations of the χ^2 fits are shown as a function of the isotopic abundance.

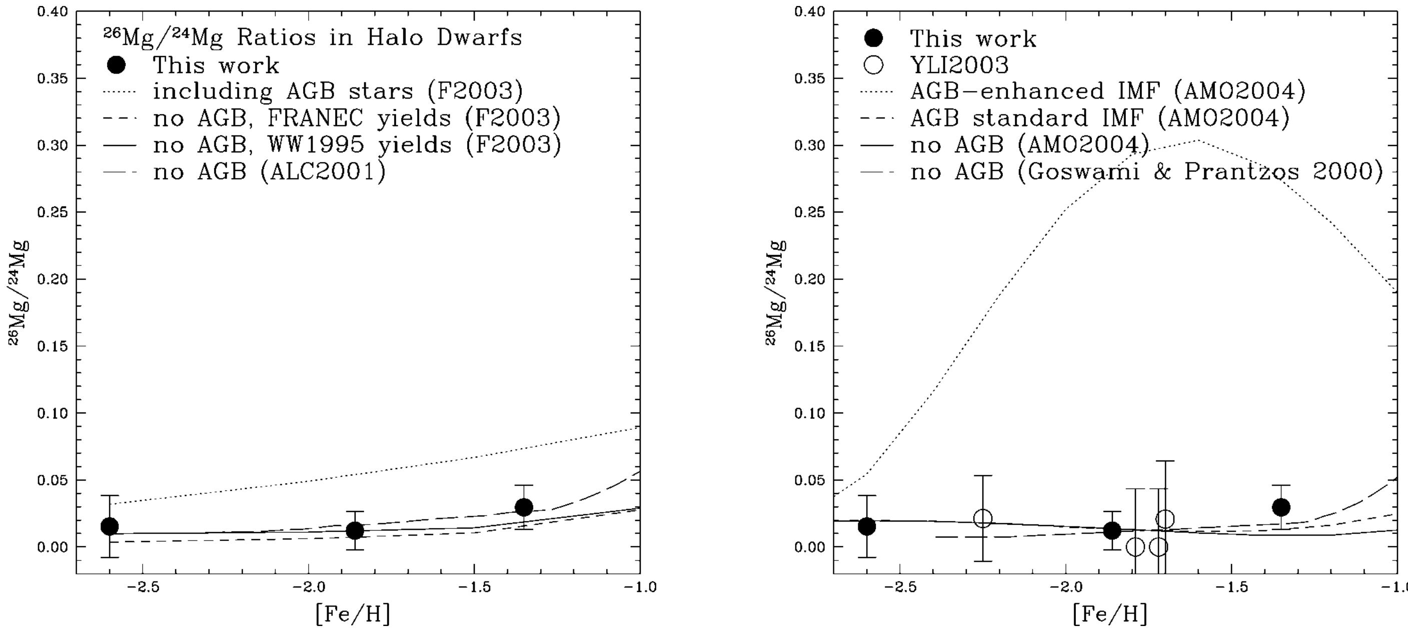

FIG. 2.—^{26}MgH/^{24}MgH as a function of [Fe/H] in halo dwarfs. Filled and open circles represent our results and those by YLI2003, respectively. All models include yields of massive stars (mostly by WW1995). Models including massive stars and intermediate-mass AGB stars (F2003 and AMO2004) are also shown. Note that AMO2004 extrapolated AGB yields for $Z < 0.004$, so their results may be unreliable. The model that agrees better with the observed data is the ALC2001 model, which does not include intermediate-mass stars.

the most metal-rich and most metal-poor stars of our sample. The results of the χ^2 fits are shown in Table 1. As can be seen, the fit by eye compares well with the χ^2 fit. The errors given in Table 1 are due to statistical errors (the standard deviation between the isotopic ratios of the three recommended regions) and systematic errors of 1% (due to errors in the atmospheric parameters; see, e.g., YLI2003). Our results for HD 103095 (^{24}Mg : ^{25}Mg : ^{26}Mg $= 94.8 : 2.4 : 2.8$) compare very well with previous visual (fitted by eye) determinations in the literature. For HD 103095, both Tomkin & Lambert (1980) and Barbuy (1985) obtained isotopic ratios of 94 : 3 : 3. More recently, Gay & Lambert (2000) determined 93 : 4 : 3.

5. DISCUSSION

Here we discuss how our isotopic ratios compare with chemical evolution models. We compare only the ^{26}Mg/^{24}Mg ratio, since the isotopic ratio for ^{25}Mg is more uncertain due to the smaller isotopic shift.

In Figure 2 (*left panel*), we compare our results with the models computed by F2003, both including and neglecting the contribution of intermediate-mass AGB stars. Another model (Alibés et al. 2001, hereafter ALC2001) that includes only massive stars is also shown. A comparison with other models (Ashenfelter et al. 2004, hereafter AMO2004; Goswami & Prantzos 2000) is shown in the right panel. As can be seen, our low isotopic ratios can be explained mostly by massive stars; thus, we find no need to invoke the contribution of intermediate-mass AGB stars at low metallicities. HD 103095 lies slightly above the predicted F2003 curve of massive star nucleosynthesis (although it is in perfect agreement with the ALC2001 model), so this may indicate that at [Fe/H] $\gtrsim -1.5$, the contribution from AGB stars begins.

The high isotopic ratios found in metal-poor stars by YLI2003 were interpreted by F2003 as an important contribution of intermediate-mass AGB stars at low metallicities. However, most of the stars with high isotopic $^{25,\,26}$Mg/Mg ratios in YLI2003 are not bona fide halo dwarfs. We computed the probability of halo membership following Bensby et al. (2003) and found that a fraction of the metal-poor stars in YLI2003 are actually thick-disk stars. Furthermore, some halo stars have abundance anomalies (e.g., CH stars), or their spectra are abnormal (e.g., double-lined), and they should be removed for a fair comparison with chemical evolution models.

After eliminating the probable thick-disk stars, as well as halo stars with anomalies, we find that only four bona fide halo dwarfs remain from the YLI2003 sample: G39-36, LHS 3780, G113-40, and G86-39. As can be seen in Figure 2 (*right panel*), the results of YLI2003 are in excellent agreement with ours.[4] We have done a similar exercise with the sample of Gay & Lambert (2000) and found that the only good unevolved halo star is HD 103095, which is already included in our sample. Lambert & McWilliam (1986) have analyzed the metal-poor ([Fe/H] $= -1.5$) subgiant ν Ind, for which they obtained only upper limits of $^{25,\,26}$Mg/Mg $\leq 3\%$.

Thus, both our results and the results of YLI2003 suggest a small (or none) $^{25,\,26}$Mg contribution of intermediate-mass AGB stars to the Galactic halo. Perhaps the $^{25,\,26}$Mg yields from AGB stars are lower than in current models (Karakas & Lattanzio 2003). If this is the case, then intermediate-mass AGB stars cannot be invoked to explain the possible variation of the fine-structure constant α (AMO2004). The chemical evolution models used to explain variations in α require an ad hoc AGB-enhanced initial mass function (IMF) in order to produce large amounts of $^{25,\,26}$Mg (AMO2004). If the correct yields are lower than present calculations, then much larger ad hoc modifications to the IMF would be required.

The calculations of Karakas & Lattanzio (2003) show that the AGB stars that contribute significant amounts of $^{25,\,26}$Mg are stars with initial masses of 3–6 $M_{\odot}$. Since these stars have

[4] YLI2003 report that G39-36 was observed with a resolving power of $R = 60{,}000$, but their other three metal-poor dwarfs were observed with a lower resolving power of $R = 35{,}000$. For G39-36, we adopted the typical error of 3% quoted by YLI2003, but for the other three dwarfs in their sample, we increased the error to 4% due to the lower resolving power of the observations.

lifetimes considerably shorter than the age of the universe, they can be used to constrain the timescale for the formation of the Galactic halo. According to the Padova evolutionary tracks,[5] the lifetimes of 3–6 $M_{\odot}$ metal-poor stars ([Fe/H] $= -1.5$) are 0.1–0.3 Gyr, so the halo timescale formation should be of the order of 0.3 Gyr. This short timescale probably explains why recent studies of age spread in Galactic globular clusters have shown that most clusters from intermediate to low metallicity are coeval within the uncertainties (e.g., Rosenberg et al. 1999; De Angeli et al. 2005).

6. CONCLUSIONS

We have shown that the ^{25,26}Mg/Mg ratios in halo dwarfs are low and that there is no need to invoke a contribution from intermediate-mass AGB stars at low metallicities.

Further high S/N high spectral resolution observation of a larger sample will help constrain the rise of AGB stars in the Galaxy and will be useful to better constrain the formation timescale of the Galactic halo.

[5] See http://pleiadi.pd.astro.it/.

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