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Cosmic Helium Production

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Abstract: K-dwarfs are very long lived, slowly evolving stars, so that their present day helium Y and metal content (metallicity Z) is essentially the same as when they were born. K-dwarfs thus contain a fossil record of the amount of helium and metals which has been produced in successive stellar generations over the lifetime of the Galaxy. We here estimate the amount of helium compared to the amount of metals produced via stellar fusion ($\Delta Y/\Delta Z$). We use K-dwarfs in the *Hipparcos* catalogue for which accurate metallicities and luminosities are available. By including recently measured K-dwarfs with super-solar metallicities we are able to obtain a very significant improvement on previous studies. The best fitting value is $\Delta Y/\Delta Z = 2.4 \pm 0.4$ at the 68% confidence level. Values as low as 1 or as high as 4 are excluded with more than 99% confidence.

Keywords: Galaxy: abundances — Galaxy: evolution

1 Introduction

The ratio $\Delta Y/\Delta Z$ — the amount of helium ΔY produced in stellar burning relative to the amount of heavier elements ΔZ — is a quantity of interest in both stellar astrophysics and cosmology. Firstly, the amount of helium in a star governs its stellar clock, i.e. how long the star will live. Secondly, helium production is a test of theoretical predictions of stellar yields: given an initial mass function (IMF) for a stellar population, $\Delta Y/\Delta Z$ is a predicted quantity of stellar evolution. Additionally, the helium in very metal-poor stars is essentially of primordial origin (i.e. produced in the Big Bang). Measuring the helium content of old stars can provide a useful constraint on cosmological models.

Constraining the amount of helium and metals produced during the lifetime of the Galaxy directly from stars themselves is not simple. Helium lines (and hence the helium abundance) can be observed directly only in very hot stars, but in these same stars the metallic lines are very weak because the stars are hot and often have strong rotational broadening. While hot stars can in principle be used to measure its helium content and its metallicity in the present-day Galaxy, such stars are very young and cannot be used to reconstruct the formation of helium and metals over the lifetime of the Galaxy. Furthermore, while metal abundances are routinely measured in long-lived (i.e. cool main-sequence) stars, measuring helium abundances in these stars is very difficult because the helium lines are so weak.

There is an indirect method to gauge the helium fraction in long-lived stars: the luminosity of a K-dwarf of a given mass depends primarily on Z and to a lesser extent upon Y. The luminosity and metallicity of K-dwarfs can be measured directly; this can then be combined with theoretical stellar models to estimate the helium content indirectly. This method of determining $\Delta Y/\Delta Z$ has been applied to stars in the solar neighbourhood using ground-based parallaxes; Perrin et al. (1977) found a value $\Delta Y/\Delta Z = 5 \pm 3$ while Fernandes et al. (1996) found $\Delta Y/\Delta Z > 2$. More recently, Pagel & Portinari (1998) have used *Hipparcos* parallaxes, infrared flux temperatures, and accurate, spectroscopically determined metallicities. They derived a value $\Delta Y/\Delta Z = 3 \pm 2$.

We (Jimenez et al. 2002) have applied a method related to that employed by Pagel & Portinari (1998) and newly available spectroscopic metallicities of stars in the *Hipparcos* sample to put tighter constraints on the value of $\Delta Y/\Delta Z$. New and accurate metallicities for K-dwarfs more metal-rich than the Sun by Thorén & Feltzing (2000) and Feltzing & Gonzalez (2001) greatly improve the final result. We find that at the 68% confidence level $\Delta Y/\Delta Z = 2.4 \pm 0.4$, a significant improvement on previous determinations.

2 Data and Analysis

The sample consists of 31 single K-dwarfs with accurate *Hipparcos* parallaxes, accurate spectroscopically determined metallicities, and broad-band V and B–V photometry. Our metallicities come from work on G- and K-dwarfs by Flynn & Morell (1997, and sources therein) and by Thorén & Feltzing (2000), Feltzing & Gonzalez (2001), Chaboyer et al. (1998), and Tomkin & Lambert (1999). The stars are in the absolute magnitude range $5.5 < M_V < 7.5$, which ensures that the effects of stellar evolution on the main sequence are negligible (i.e. upper luminosity cut at $M_V = 5.5$), that and the luminosity predictions of the stellar models are reliable (i.e. the lower luminosity cut at $M_V = 7.5$). Figure 1 shows the sample

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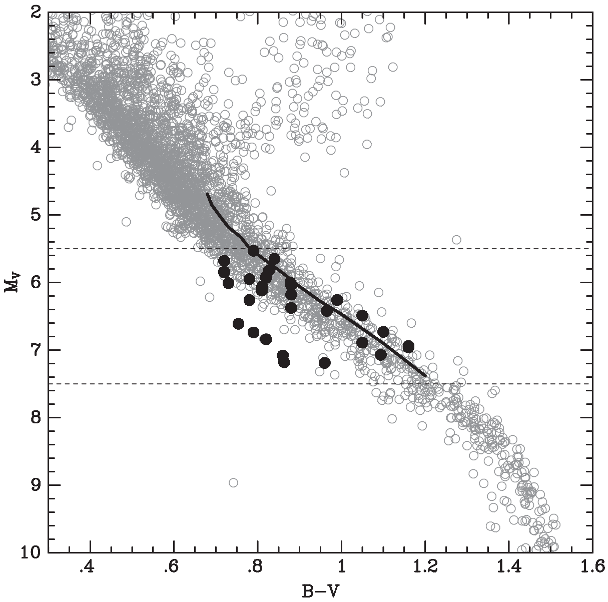

Figure 1 Our sample of K-dwarf stars (solid symbols) plotted over the *Hipparcos* colour–magnitude diagram (grey symbols). The reference isochrone JFK0 is shown by the solid line. The difference between a star's luminosity M_V and the luminosity of the isochrone at the same colour is the quantity ΔM_V, which correlates tightly with the stellar metallicity in Figure 2. There are a small number of stars standing out a few tenths of a magnitude above the main sequence which are likely to be unrecognised binaries.

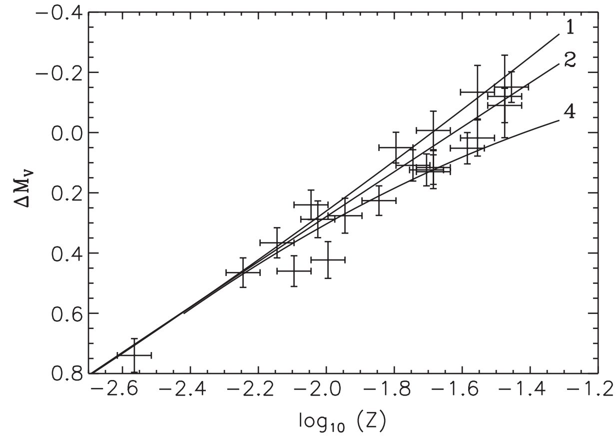

Figure 2 The solid lines shows ΔM_V, computed as a function of metallicity Z for theoretical models for K-dwarfs for different values of $\Delta Y/\Delta Z$ (1, 2, and 4, running from top to bottom). The observational points are for K-dwarfs with *Hipparcos* parallaxes (see text), and accurate, spectroscopically determined metallicities. Note that $\Delta Y/\Delta Z = 4$ is not a good fit. Careful fitting yields $\Delta Y/\Delta Z = 2.4 \pm 0.4$ at the 68% confidence level.

in the *Hipparcos* colour–magnitude diagram along with a solar metallicity isochrone termed JFK0 (solid line), computed from our models.

We denote the difference between the absolute magnitude of a given star and this isochrone at the same B–V colour as ΔM_V. This quantity is primarily correlated with metallicity, as first shown in Kotoneva et al. (2002), but also has a dependence on the assumed helium content in the model (cf. Figure 2).

We have computed ΔM_V theoretically using K-dwarf stellar models over a range of helium and metallicity compositions Y, Z and four adopted values for $\Delta Y/\Delta Z = 1, 2, 3, 4$. We use the stellar evolution code JMSTAR developed by one of us (J. MacDonald) to compute isochrones for the range of M_V of interest, $5.5 < M_V < 7.5$, and colours, $0.4 < B\text{–}V < 1.4$, or equivalently effective temperatures, $6000 < T_{\rm eff} < 4500$. In brief, the code incorporates state of the art understanding of convection, opacity values, nuclear reaction rates, and equation of state. JMSTAR is based on a Henyey approach, where the entire star is divided into concentric shells including boundaries at the centre and surface. Once the shells and boundary conditions are chosen, the stellar structure equations are approximated by finite difference equations. During the various stages of evolution, the grid of shells is allowed to evolve using an adaptive mesh technique. This requires an extra pair of differential equations that describe how changes in the variables across a shell are to be controlled. The code uses OPAL opacities (Iglesias & Rogers 1996) for temperatures greater than 7000 K. At lower temperatures, we evaluate Rosseland mean opacities by interpolating with respect to $\log T$ and $\log R'$ (where $R' \equiv \rho/T^3$) in the table of opacities reported by Alexander & Ferguson (1994) for $Y = 0.28$, $Z = 0.02$, supplemented by tables kindly supplied by D. R. Alexander (private communication) for $Y = 0.24$ and $Z = 0.0002$, 0.005, 0.001, and 0.004. The equation of state includes the H_2 molecule and all ionisation states of H, He, C, N, and O, plus a representative heavier element. Pressure ionisation and electrostatic terms are included. Mixing length theory (Mihalas 1978) is used for convection. The diffusion approximation is used for radiative transfer throughout. The nuclear reaction network involving ^{3}He is definitely not in equilibrium, so we use a fully time-dependent prescription for this network. We include electron screening effects in the nuclear reaction rates, due to the high gas densities in the cores of low-mass stars.

The code has been used successfully for a number of problems, but here we only need it for a much simpler task: to compute stellar tracks on the main sequence for stars with masses $0.6 < M/M_\odot < 1.2$, allegedly the best understood part of stellar evolution. Note that we are not using stars with mass below $0.5\,M_\odot$ where H_2 opacity becomes significant, and also the colour–temperature relation is not as accurate as for higher mass stars.

We compute stellar isochrones and convert from the theoretical $(L - T_{\rm eff})$ to the observational plane $(M_V - (B\text{–}V))$ using the most recent Kurucz atmosphere models. We use the fiducial solar isochrone of Kotoneva et al. (2002) as our reference point to measure ΔM_V for the model stars at a colour of $B\text{–}V = 0.9$, which corresponds to $M_V = 6.06$. Figure 2 shows the expected ΔM_V versus $\log Z$ relation compared to the sample stars. The three curves represent our theoretical expectations for $\Delta Y/\Delta Z = 1$, 2, and 4. Firstly, for sub-solar metallicities,

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the fit is excellent: In these stars there is so little additional helium above the primordial amount Y_p that $\Delta Y/\Delta Z$ plays virtually no role. While the luminosity of the stars is primarily sensitive to metallicity, we also confirm our expectation that the effect of helium content Y is only seen when the metallicity is sufficiently high. Note that the primordial abundance was chosen to be $Y_p = 0.235$, so that at $Z/Z_\odot = 0.3$ the corresponding values of Y are 0.243, 0.251, and 0.267 for $\Delta Y/\Delta Z = 1$, 2, and 4, respectively: i.e. these are sufficiently different in Y to have an effect on the luminosity of the star.

Even by eye one can see that models with $\Delta Y/\Delta Z$ as high as 4 are ruled out by the high metallicity stars. In order to obtain the statistical significance of the best fitting model, we have performed a maximum likelihood fit of the data to the models. The errors are Gaussian distributed and uncorrelated, so this translates into simple χ^2 statistics. Our best fit is obtained by minimising χ^2 and yields a value of $\Delta Y/\Delta Z = 2.4 \pm 0.4$ at the 68% confidence level. This is the internal error in the fitting of the models to the data — realistically, there are likely to be sources of systematic error which are of the same order as the internal error. Nevertheless, the accuracy we attain is a significant improvement on previous work, which constrained $\Delta Y/\Delta Z$ to lie in the range 1–5.

3 Discussion

Our estimate of $\Delta Y/\Delta Z$ can easily be improved by obtaining spectroscopic abundance estimates for more metalrich stars in the solar neighbourhood, and also by obtaining accurate colours for our sample stars (L. Casagrande & C. Flynn, in preparation). Candidate metal-rich stars can be found a few tenths of a magnitude above the JFK0 isochrone (see Figure 1) in the colour–magnitude diagram (although there will also be significant contamination in this part of the colour–magnitude diagram by multiple stars). The B–V colour errors of our stars dominate the error budget because of the steep slope of the main sequence in the colour–magnitude diagram.

Our results depend on the luminosity predictions of our stellar models, and can be checked by comparing with observed luminosities of K-dwarfs of known mass and metallicity. We are currently investigating whether there are sufficiently accurate data for K-dwarfs in binary systems to verify the model luminosity predictions directly.

The low metallicity stars in Figure 2 permit an indirect determination of the primordial helium abundance Y_p as the helium content of the stars with [Fe/H] < -1.0 should be very close to primordial. We estimate $Y_p = 0.24 \pm 0.01$ from the data analysed here; as for the metal-rich stars, targeted photometric data for halo K-dwarfs in the *Hipparcos* sample should allow us to improve this estimate in the near future. Presently, estimates of Y_p lie in the range 0.238–0.245 (typically estimated on the basis of helium abundances in H II regions, see e.g. Peimbert et al. 2003; Luridiana 2003). Cosmic microwave background results alone from the Wilkinson Microwave Anisotropy Probe (*WMAP*) constrain primordial helium to $0.16 < Y_p < 0.50$ (Trotta & Hansen 2003); combining *WMAP* 's results with other astrophysical constraints (i.e. assuming that there are three neutrino species and the baryonic matter density Ω_b is fixed via the observed deuterium abundance) leads to $Y_p = 0.248 \pm 0.001$ (Barger et al. 2003). Observational measurements of Y_p at this level of accuracy (0.001) from either H II regions or K-dwarfs would be able to significantly constrain cosmological parameters; at present such measurements are dominated by systematic errors at about the 0.01 level.

There are currently a number of space-based asteroseismology missions either just launched (*MOST*) or in the planning stages (e.g. COROT, *Rømer*/MONS, *Kepler*, and *Eddington*), so that helium fractions for nearby stars will soon be measurable through stellar oscillations. Astroseismology of K-dwarfs in particular would be of interest, as such observations should be able to significantly improve on the measurements of Y_p reported here, and perhaps map out in detail the development of helium in the interstellar medium as a function of metallicity (we have here merely constrained its gradient, $\Delta Y/\Delta Z$).

Acknowledgements

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