FINE STRUCTURE IN THE MAIN SEQUENCE: PRIMORDIAL HELIUM AND $\Delta Y/\Delta Z$

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Abstract. The primordial helium abundance Y_P is important for cosmology and the ratio $\Delta Y/\Delta Z$ constrains models of stellar evolution. While the most accurate estimates of both quantities now come from emission lines in HII regions, significant information comes from effects of helium content on stellar structure including in particular the location of the main sequence as a function of metallicity and age. HIPPARCOS parallaxes with 1 or 2 mas accuracy will naturally lead to great advances in this type of study for stars with metallicities down to about 0.1 solar, but sub-mas accuracy will be needed in order to extend it to stars of still lower metallicity.

1. Introduction

One success of Big-Bang cosmology has been to predict primordial abundances of light elements (Walker *et al.* 1991; Smith *et al.* 1993); but precise determination of each primordial abundance involves difficulties, both from measurements and in extrapolating through evolution that has taken place in the meantime. While overall agreement with Big-Bang theory is not in doubt, detailed consequences such as the exact limits on baryonic and non-baryonic matter remain controversial.

Fig 1 shows the region of concordance usually accepted for primordial abundances (tall continuous vertical lines) with resulting limits on the density parameter $\Omega_{b0}h_0^2$; Ω_{b0} is the fraction of closure density from baryons now and h_0 is the Hubble constant in units of 100 km $s^{-1}Mpc^{-1}$. BDM and NDM show implied amounts of baryonic and non-baryonic dark matter. These conventional values have, however, all been challenged for various reasons (*cf.* Pagel 1994ab), resulting in the much wider limits shown by the broken lines in the figure, so any supplementary evidence can be useful.

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Astronomical and Astrophysical Objectives of Sub-Milliarcsecond Optical Astrometry, 181–186.

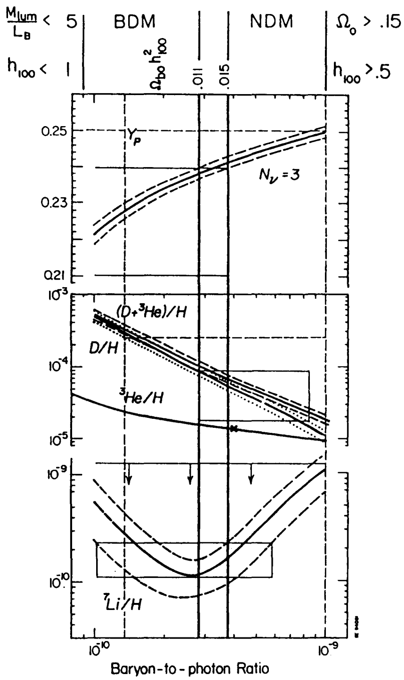

Figure 1. "Optimistic" (narrow) and "pessimistic" (wide) estimates of limitations placed on the baryonic density parameter $\Omega_{b0}h_0^2$ from adopted upper limits to primordial abundances of light elements, notably ^{4}He and deuterium.

2. Y_P and $\Delta Y/\Delta Z$

Numerous estimates of the primordial helium mass fraction Y_P (see Table 1 and detailed references in Shaver *et al.* 1983 and Pagel 1994a) agree at the 10 per cent level, but systematic errors make it difficult to achieve the precision of a few per cent needed to constrain the Big Bang. The smallest error estimates are those for the method based on extragalactic HII regions, in which one plots a regression of He against O (or N) from measurements of emission lines and extrapolates to zero O (or N). Rather little extrapolation is actually needed, but there could be additional systematic errors.

The quantity $\Delta Y/\Delta Z$ represents the amount of additional helium ejected by dying stars relative to the ejected amount of heavy elements from carbon upwards. It can be predicted from the theory of stellar evolution, assuming an initial mass function (IMF), needed because while Z comes mainly from massive stars undergoing supernova explosions, most of the additional helium comes from intermediate-mass stars (typically $5M_\odot$) which lose mass in winds and planetary nebulae. It is found observationally either from the slope of the regression of He against O in HII regions or by considering effects of helium on stellar structure and evolution.

TABLE 1. Primordial Helium (ESO 1983 *et al.*)

	Y_P	Method	First author	Problems
Sun	$< .28 \pm .02$	Interior	Turck-Chièze	κ; eq of st; ν problem
Sun	$< .28 \pm .05$	Prom. HeI	Heasley	Level pops.
B-stars	$< .30 \pm .04$	Abs. lines	Kilian	Precision
μ Cas	$.23 \pm .05$	Bin. orbit	Haywood	Precision
Subdw.	$.19 \pm .05$	Main seq.	Carney	Plx.; $T_{\rm eff}$; conv.
Glob-	.23 :	RR, Δm	Caputo	Physical
ular	$.23 \pm .02$	N(HB)/N(RG)	Buzzoni	basis of
clus-	$.20 \pm .03$:	"	Cole	stellar
ters.	$.23 \pm .02$:	HB morphology	Dorman	evolution
Galactic	$.22 \pm .02$	Plan. neb.	Peimbert	Enrichment
nebulae.	.22 :	HII regions	Mezger	He^0; enr.
Extra-	$.233 \pm .005$	Irr.+BCG	Lequeux	He^0; data
galactic	$< .243 \pm .010$	BCG	Kunth	IIZw40
HII	$.228 \pm .005$	Irr.+BCG	Pagel	?
regions	$.232 \pm .003$	"	Olive	?

While conventional stellar evolution calculations give $\Delta Y/\Delta Z \simeq 2$ or less (Maeder 1992, 1993), observations give larger values, e.g. ~ 3.5 (Faulkner 1967), 5 ± 3 (Perrin *et al.* 1977) from main sequences and 3 ± 0.5 (Lequeux *et al.* 1979; Peimbert 1993) and 4 ± 1 (Pagel *et al.* 1992) from HII regions. Explanations for this discrepancy include (i) a low upper limit ($\simeq 25 M_\odot$) to the initial mass of stars undergoing supernova explosions as opposed to going into black holes; (ii) loss of Z-elements by selective galactic winds following bursts of star formation in dwarf galaxies; (iii) underestimation of oxygen abundance in HII regions by neglecting electron temperature fluctuations; and (iv) that a steep IMF (Scalo 1986) gives a value of 3 for a supernova upper mass limit of about $50 M_\odot$ (Maeder 1992). Since some of these explanations are specific to HII regions and dwarf galaxies and others more general, the importance of improving the stellar data becomes clear.

3. Effects of helium on stellar structure

Various effects of initial helium content on the evolution of stars in globular clusters are briefly summarised in Table 1. The zero-age main sequence follows quasi-homology relations; e.g. Faulkner (1967) gives:

$$L \propto (X + 1.2)^{-11.72} \, (Z + 0.012)^{-0.134} \, M^5 \tag{1}$$

for the mass-luminosity relation, and

$$L \propto (X+0.4)^{2.67}\,(Z+0.010)^{0.455} f(T_e) \tag{2}$$

for the main sequence, where X is the mass fraction of hydrogen and T_e the effective temperature. Similar relations can be derived from more modern evolutionary tracks. The mass-luminosity relation can now almost be modelled in absolute terms, given modern opacities, whereas the main-sequence relation is subject to uncertainties in convection theory and fitting model atmospheres and must in practice be calibrated assuming a certain helium abundance for the Sun, allowing for any physical and chemical changes.

Assuming these problems to be overcome, one can make an error budget for the derivation of X from either of these relations. In the first case, assuming that the mass is derived from an interferometric binary orbit as in the case of μ Cas, the major uncertainties are the distance D and the angular major axis α of the relative orbit, while the exact value of Z is not important if it is small. The resulting error budget from eq (1) is

$$\frac{\delta X}{X+1.2} = 1.11\,\frac{\delta D}{D} + 1.28\,\frac{\delta\alpha}{\alpha} \tag{3}$$

or

$$(\delta X)^2 \simeq (2\,\delta D/D)^2 + (2.5\,\delta\alpha/\alpha)^2, \tag{4}$$

since $X \simeq 0.75$. Thus a parallax good to 1 per cent already leads to an error of 0.02 in X or Y and there is a still stricter requirement on α.

The error budget for the main sequence is more favourable (not counting uncertainties in the physics). Here the major uncertainties are in the distance and in the effective temperature. Taking $f(T_e) \propto T_e^7$, we have

$$\frac{\delta X}{X+0.4} = 0.75\,\frac{\delta D}{D} - 2.6\,\frac{\delta T_e}{T_e} \tag{5}$$

or

$$(\delta X)^2 \simeq (0.9\,\delta D/D)^2 + (3\,\delta T_e/T_e)^2. \tag{6}$$

Models for low-metallicity stars aged 15 Gyr and with $\log T_e = 3.72$ (e.g. VandenBerg 1983) give a quasi-homology relation like eq (2) only with $(Z+0.003)$ instead of $(Z+0.010)$, but the error budget is otherwise identical. The demand on accuracy in distance is less severe by more than a factor of 2 than for the mass-luminosity relation, although there are now stringent requirements on the accuracy of T_e and reddening effects if any.

Thus most estimates of helium in metal-deficient field stars have come from main-sequence fitting. From eq (2) it follows that, at high Z, reduction of helium and Z act in opposite directions and may compensate each other,

TABLE 2. Nearby subdwarfs with $Z < 0.1 Z_\odot$

HD	π mas	$\delta D/D$, per cent ground	LK	Hipparcos 1.5 mas	Rømer etc. 0.1 mas
103095	116 ± 5	4	1	1.3	0.1
25329	54 ± 5	9	4	2.8	0.2
201891	41 ± 6	15	12	3.7	0.25
134439-40	40 ± 5	12	6	4.0	0.25
64090	38 ± 4	11	12	4.0	0.25
193901	35 ± 6	17	17	4.3	0.3
84937	25 ± 5	20	31	6.0	0.4
108177	30 ± 7	23		5.0	0.35
94028	23 ± 7	30		5.0	0.45
19445	21 ± 6	29		7.1	0.5

whereas at low Z a decrease in helium leads to a raising or rightward shift of the main sequence independent of Z. Perrin *et al.* (1977) could find no metallicity-correlated dispersion in the main sequence of nearby disk stars and from this they deduced $\Delta Y/\Delta Z = 5 \pm 3$, a number that will certainly be greatly improved when HIPPARCOS parallax data become available and can be used in conjunction with modern, accurate opacities.

The extension of such considerations to extremely metal-deficient stars associated with the Galactic halo is considerably more challenging. Carney (1979, 1983) used ground-based parallaxes of a few extreme subdwarfs having $Z < 0.1 Z_\odot$ with modified Yale isochrones to deduce $Y_P = 0.19 \pm 0.05$, a result that is marginally discrepant with other data in Table 1 and subject to numerous uncertainties, of which that in the distances is by no means the least significant. The problem can be seen from Table 2.

The first column gives HD numbers for the nearest stars with $Z < 0.1 Z_\odot$, the ones above the gap being the nine considered by Carney (1983) omitting the subgiant HD 140283. The second column gives parallaxes with standard errors, from the HIPPARCOS Input Catalogue. The third column gives the corresponding percentage error in distance, which according to eq (6) translates into about the same number of units in the second decimal place of the resulting error in Y, i.e. the error is ± 0.04 for the uniquely favourable case of HD 103095 = Groombridge 1830 and unbearably large for all the others. The fourth column gives the Lutz-Kelker correction applied by Carney, which is also highly significant; full applicability of this correction to stars selected by proper motion is not completely clear (Hanson 1979; Lutz, Hanson & Van Altena 1987), so that this adds further uncertainties. Thus with only existing ground-based parallaxes available, the enterprise of trying to estimate primordial helium from the subdwarf main sequence was doomed from the start.

The fifth column gives percentage errors in distance expected from HIPPARCOS parallaxes with a standard error of ±1.5 mas (Perryman 1994). Surprisingly, perhaps, the situation here is still quite unsatisfactory, with errors in X or Y of ±0.03 and more, just from the distance, in all cases except Gmb 1830. The last column shows the precision obtainable from parallaxes with 0.1 mas errors, which one hopes may result from future space or interferometric projects; only in this case do the distance errors become negligible so that one can concentrate on the purely astrophysical problems.

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