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PRIMORDIAL ^{4}He AS A TEST OF BIG BANG NUCLEOSYNTHESIS

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ABSTRACT

We discuss how Y_p, the observationally inferred primordial ^{4}He abundance, becomes a stringent test of both the standard homogeneous and inhomogeneous big bang models. We argue that the standard procedure of extrapolating the straight line fit to the ^{4}He data to obtain the zero metallicity intercept is inappropriate and places inordinate weight on high-metallicity points. Extrapolating lower metallicity data versus N, we obtain $Y_p = 0.220 \pm 0.010$. At face value, this result just precludes the standard model with three light neutrinos and places severe constraints on inhomogeneous models. However, systematic errors are potentially large, and therefore no definitive conclusion can be reached at this time.

Subject headings: abundances — cosmology — nucleosynthesis

A number of models of primordial nucleosynthesis have been proposed, including the standard homogeneous model (SM) (Wagoner, Fowler, & Hoyle 1967; Schramm & Wagoner 1977; Yang et al. 1984), the inhomogeneous models (IM) (Applegate, Hogan, & Scherrer 1988; Alcock, Fuller, & Mathews 1987; Fuller, Mathews, & Alcock 1988; Malaney & Fowler 1988; Kajino & Boyd 1990; Mathews et al. 1990; and Kurki-Suonio et al. 1988), and decaying particle models (Audouze et al. 1983; Fukugita, Kawasaki, & Yanagida 1989; Dimopoulos et al. 1988). The SM and IM have three parameters in common which characterize nucleosynthesis: the entropy per baryon, the universal expansion rate during nucleosynthesis, and the neutron lifetime. The entropy can be parameterized by the fraction of the closure density contributed by baryons, Ω_b, once the cosmic photon background temperature has been set. The expansion rate at the nucleosynthesis epoch is determined by the energy density in photons, electrons, baryons, and any additional degrees of freedom, parameterized by the equivalent number of relativistic neutrino species N_ν.

Recent experiments have tightly constrained two of these quantities. The Z^0-width experiments (ALEPH et al. 1990) yield $N_\nu = 2.98 \pm 0.06$. This experiment is sensitive to any neutrino with a mass less than about half the Z_0 mass. If the three neutrinos are identified with ν_e, ν_μ, and ν_τ, then if ν_μ and ν_τ are unstable, either or both could be nonrelativistic during the nucleosynthesis epoch. This would affect the energy density, hence nucleosynthesis (Kolb & Scherrer 1982). The measurement of Mampe et al. (1989), together with others, gives the neutron lifetime $\tau_n = 889.8 \pm 4.4$ s (Olive et al. 1990). Thus only Ω_b remains unconstrained by experiment. In the SM, the demand that the primordial ^{7}Li abundance be that observed in Population II halo stars, and the constraints on D + ^{3}He (Boesgaard & Steigman 1985), define a narrow range in allowed baryon density, $\Omega_b h^2 \approx (0.011\text{–}0.016)$ (Kawano et al. 1990; Schramm 1990), where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}. The three light neutrinos, $\tau_n = 889.8 \pm 4.4$ s, and the constraint on Ω_b give a lower limit for the calculated primordial ^{4}He abundance in the SM of $Y_p = 0.235$ (Olive et al. 1990). An observationally inferred Y_p less than this would present a serious problem for the SM, as discussed by Pagel (1990).

The primordial abundances from the IMs depend on several quantities besides the three discussed above, including the amplitudes, separations, filling factors, and overall geometry of the baryon number fluctuations (Mathews et al. 1990). Although none of these quantities can be reliably estimated, several signatures of inhomogeneity have been proposed, including abundances of ^{7}Li, ^{9}Be, and some intermediate-mass and r-process elements (Applegate et al. 1988; Mathews et al. 1990; Kajino, Mathews, & Fuller 1990; Boyd & Kajino 1989; Kawano et al. 1990).

However, Alcock et al. (1990) have shown that it is very difficult to calculate the yield of ^{7}Li in the IMs, as the time scale for hydrodynamic expansion of the fluctuations during the nucleosynthesis epoch may be shorter than that for the nuclear reactions, leading to destruction of ^{7}Li. In some IMs, the ^{7}Li abundance may actually be below that of the SM. Given these considerations, along with the complicated and controversial production and astration history of ^{7}Li in the galaxy (Mathews et al. 1990), we conclude that ^{7}Li is not yet a good constraint on primordial inhomogeneity. Similarly, although ^{9}Be and intermediate-mass elements are promising, either their nucleosynthesis is too poorly understood or the observational problems involved in determining their primordial abundances are too great for them to provide useful constraints.

The primordial ^{4}He abundance, however, stands in contrast to these nuclides as a signature for nucleosynthesis-epoch inhomogeneity. At a given Ω_b, some IMs can produce up to 6% less ^{4}He than does the SM (Mathews et al. 1990). Unlike ^{7}Li and some other light elements, the calculated Y_p value in IMs is unaffected by late-time hydrodynamic phenomena because the temperature during hydrodynamic expansion is too low to affect ^{4}He production or destruction. The Galactic chemical evolution of ^{4}He is much less complicated than that of other light elements, since it is not as fragile. These considerations, along with the minimum Y_p value in the SM discussed above, suggest that its accurate determination might produce a crucial test among the SM, IM, and other alternatives.

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Traditionally Y_p has been determined by a linear regression fit of ^{4}He versus metallicity (either O or N) extrapolated to zero metallicity (cf. Pagel 1982, 1990), although there is no reason to believe that the ^{4}He abundance has always increased linearly with that of O or N. Indeed, extrapolation of such a fit could provide a very misleading value for the primordial abundance (Pagel 1990). If the linear regression procedure is carried out for all existing ^{4}He-metallicity data, including that from the Sun, Orion, and other high-metallicity sources, then the primordial intercept derived is $Y_p \approx 0.24 \pm 0.01$ (Pagel 1990; Baldwin et al. 1990). Pagel (1990), however, has drawn attention to an interesting trend in the ^{4}He data. If one restricts the fit to low-metallicity extragalactic H II region data, then the slope of the line may be steeper than for the general fit, thus yielding a smaller Y_p. Pagel derives $Y_p = 0.225 \pm 0.005$ using this procedure (versus O) when the data set is restricted to metallicity less than 0.25 of solar. We note that the existence of such a trend is controversial; Kunth & Sargent (1983) see no statistically significant trend in their ^{4}He data, while Peimbert & Torres-Peimbert (1976) do in theirs. This problem is discussed in Boesgaard & Steigman (1985). There may be theoretical grounds for expecting a different ^{4}He metallicity slope for low-metallicity environments early in the evolution of a galaxy than for high-metallicity environments characteristic of the last few billion years of chemical evolution.

Indeed, the ratio of He-to-metallicity yield ($\Delta Y/\Delta Z$) is a complicated function of stellar mass and composition (cf. Chiosi & Maeder 1986; Woosley & Weaver 1986). In the models of Woosley & Weaver (1986) $\Delta Y/\Delta Z$ ranges from 0.08 for a 35 $M_\odot$ star to 0.7 for a 15 $M_\odot$ star, while their 10 $M_\odot$ model made ^{4}He but almost nothing else. The relation for $\Delta Y/\Delta Z$ is not even monotonic with mass. Averaging over an initial mass function (IMF) shows that most heavy elements are made in stars with $M > 30\ M_\odot$, most of the stellar-produced ^{4}He comes from stars with $M < 30\ M_\odot$, and most of the C and N comes from stars of intermediate mass (Chiosi & Maeder 1986). Such averaging over a conventional IMF yields $\Delta Y/\Delta Z \approx 1.3$, whereas this quantity inferred from the extragalactic H II region data is closer to 3.0 (Peimbert & Torres-Peimbert 1976). While the calculations of Woosley & Weaver (1986) and of Chiosi & Maeder (1986) assumed much higher metallicities than would be expected from primordial nucleosynthesis, their results do show the sensitivity of $\Delta Y/\Delta Z$ to stars of different mass, and hence to the IMF. Thus an IMF which is much different from the present one, as that of the early galaxy might well have been, could have a dramatic effect of $\Delta Y/\Delta Z$; a radically different value thereof from that of the present universe should therefore not be surprising.

Nonetheless, ^{4}He, ^{12}C, and ^{16}O would be made in first generation stars, the former through *p-p* chain burning, if insufficient C existed to catalyze the CNO cycle, and the latter two in the ^{4}He-burning stage. By contrast, appreciable N would be observed in the ISM only after second generation stars made N in their H-burning phase via the CNO cycle and then exploded: O is primary and N is secondary. The result of this delayed N synthesis is a more gradual increase in N abundance with time than would be expected, e.g., for O. This effect has been observed (Clegg, Lambert, & Tompkin 1981; Andreani, Vangioni-Flam, & Audouze 1988). Thus, since He production begins with first-generation stars, the He to N abundance curve should increase fairly rapidly initially, then slow to a lower rate of increase as the CNO cycle both assumes dominance as the source of ^{4}He production and also begins to produce N. Thus, the general shape of the curve describing the ^{4}He versus N abundances should be predictable for low N abundance. However, since the ^{4}He to O curve must depend strongly on the details of the poorly known IMF of the early galaxy, its general shape is considerably more difficult to predict from basic considerations. Note, though, that if ^{4}He data could be obtained for very metal poor regions, O might well be the best reference nuclide because of its rapid rise with time.

Because of the predictability of the general shape of the ^{4}He versus N curve for low N, and the unpredictability of that for ^{4}He versus O, we have focused our efforts to determine Y_p by comparing the ^{4}He to N abundance. We have used data for H II regions tabulated by Pagel (1990), which are shown in Figure 1. Fits to different subsets of the data were performed, using the linear regression procedure (Lyons 1986) for data with two-dimensional error bars. Extrapolation to zero metallicity then gave Y_p for each data subset. As the subset approached zero in the N abundance, the slope of the fit was found to increase. The fit to all 41 points (some of which represent many data points) gives an extrapolated He abundance of $Y_p = 0.233 \pm 0.009$, in general agreement with that obtained by other authors (Pagel 1987; Baldwin et al. 1990). However, the fit to the first 22 points gives $Y_p = 0.221 \pm 0.007$, while that to the first 14 points gives $Y_p = 0.220 \pm 0.007$. We note again

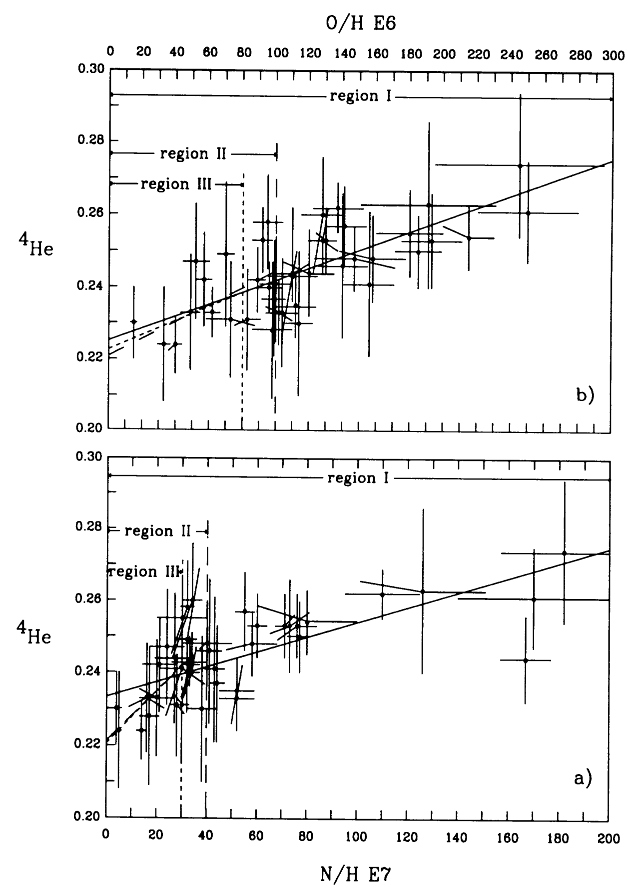

FIG. 1.—The ^{4}He abundance as a function of the O abundance (*upper*) and as a function of the N abundance (*lower*). The various straight lines represent fits to the regions indicated. Note that the slope of the straight line fit increases as the subset of points fitted approaches the ordinate for the He-N graph plot but is fairly constant for the He-O plot.

that the highest metallicity stars in these data have considerably lower metallicity than the Sun.

We assert that this suggests an upper limit on the He *abundance at the beginning of the galaxy of around $Y_p = 0.220$.* Given the shape of the He versus N curve which would be expected from the very basic considerations discussed above, the intercept given by the straight line extrapolation would have to give an upper limit on the He abundance at the beginning of the galaxy, and hence, on Y_p. If more data existed for low-N abundance environments, the fit to them would be expected to give an even lower upper limit. We note that, if very massive Population II stars constituted the first generation of stars, the upper limit on Y_p so obtained could be considerably higher than the actual Y_p value. This results from the ability of very massive stars to expel ^{4}He-rich winds (Bond, Arnett, & Carr 1984) during their main-sequence phase, yet produce virtually nothing else because their subsequent pair instability–induced collapse might carry all the heavy element synthesis into a black hole. Pregalactic stars could thus produce up to several percent of the ^{4}He without conflicting with any nycleosynthesis bounds (Bond et al. 1984).

The He versus O data of Pagel (1990) are also shown, together with several straight line fits, in Figure 1. The straight line extrapolation obtained by fitting all of the points gives $Y_p = 0.225 \pm 0.008$, that to the first 17 points $Y_p = 0.221 \pm 0.009$, and that to the first nine points $Y_p = 0.222 \pm 0.009$. The constancy of these values appears to confirm, albeit with marginal statistics, our suspicion that the high O production early in the life of the galaxy makes it difficult to obtain data from an epoch in which the He-to-O ratio was rising rapidly, if such ever existed.

While the uncertainties (1 σ) on the extrapolated values are about 0.007, the systematic uncertainties may be larger. Pagel (1982, 1990) notes that several such sources may exist in the H II regions from which the data are derived, including corrections for neutral ^{4}He, uncertainties in ionizing UV flux, processes involving grains, and interstellar reddening and absorption lines of metals. These error sources are reviewed in Davidson & Kinman (1985). Some of these can be minimized by using data from extragalactic H II regions, specifically those in irregular and compact blue galaxies where the metallicity is globally low and the ionizing UV flux is believed to be large enough that the correction for neutral ^{4}He is small (Lequeux et al. 1979; Kunth & Sargent 1983; Peimbert & Torres-Peimbert 1976; Pagel & Simonson 1989). Corrections for collisional excitation of He I lines have been made (Pagel 1990), but are also uncertain (Ferland 1986; Pagel 1987; Berrington & Kingston 1987; Clegg 1987; Aller 1990). Such effects may increase the uncertainty to about 0.01 (Pagel 1990), or even 0.02 (Davidson & Kinman 1985). It will be difficult to refine the value of Y_p to better than that until the systematic effects are better understood.

We emphasize again that the Y_p value we obtain by extrapolation is an upper limit, due to the general shape of the ^{4}He versus N curve. While it would obviously be preferable to simply have ^{4}He data at sufficiently low metallicity that extrapolation is not necessary, the present procedure will have to suffice until such data are available. We encourage observers to seek out metal-poor objects in order to obtain those critical data.

As noted above, the lowest value of Y_p allowed by the SM, assuming three light neutrino flavors and the neutron lifetime of 889.8 ± 4.4 s, is $Y_p = 0.235$ (Olive et al. 1990). While this is only slightly outside the value of $Y_p = 0.220 \pm 0.010$ we obtain, we note again that our value represents an upper limit. Thus it is important to consider the implications of this apparent disagreement. A lower assumed density of the universe would produce a lower predicted ^{4}He abundance. However, with as low a primordial ^{4}He abundance as 0.220, the SM does not satisfy the primordial abundance constraints (Boesgaard & Steigman 1985) for ^{2}H, ^{3}He, ^{4}He, and ^{7}Li for any density. One can envision fixes for the SM, e.g., decreasing the energy density during nucleosynthesis by demanding an unstable ν_τ with mass greater than 200 keV (Kolb & Scherrer 1982).

A value of $Y_p = 0.220$ would also place limitations on the IMs discussed above. These models can produce a Y_p value as low as 0.220, but only with a baryonic density less than about 20% of the closure density. *In neither model is a closure density in baryons consistent with the presently derived* ^{4}He *abundance.* Late-decaying particle models can be tuned to produce ^{4}He in a broad range, even with Ω_b of 1, but may suffer from overproduction of ^{6}Li (Dimopoulos et al. 1988).

In summary, the ^{4}He abundance plotted versus the N abundance appears to exhibit a larger slope at low-N abundance than it does throughout the rest of the graph. While the statistical significance of this feature can be argued, we claim that our approach is the proper one to use in fitting the ^{4}He data. *Fitting any but the low-metallicity points is irrelevant to determination of the primordial* ^{4}He *abundance, as the high-metallicity points would not be expected to exhibit either the value of Y_p or the slope from which to obtain it.* Furthermore, considerations of basic features of nucleosynthesis of first-generation stars suggest that the primordial ^{4}He abundance is less than about $Y_p = 0.220$. This result suggests that future improvements in data and analysis of the processes discussed here may yield a crucial discriminator between standard and nonstandard nucleosynthesis models.

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