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Contamination of Primordial Helium in Galaxies*

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The cosmic abundance of ^{4}He provides a fundamental test of the standard hot big bang model. In this Comment we discuss the importance of proper corrections for contaminating helium produced by stars when inferring the primordial ^{4}He abundance from observations of gas in galaxies. These corrections have traditionally relied on oxygen as a tracer of the degree of stellar processing, which ignores the possibility that excess helium is produced by intermediate mass stars that do not make oxygen. A modest extension of the simple galactic chemical evolution model is proposed in which carbon or nitrogen abundances are combined with oxygen abundances to give a more robust measure of stellar helium contamination levels in metal-poor galaxies.

Key Words: *cosmology, chemical evolution, abundances*

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1. INTRODUCTION

The abundance of primordial ^{4}He provides a crucial test of the standard (isotropic, homogeneous, 3 families of light neutrinos) hot big bang cosmological model. Furthermore, the primordial ^{4}He abundance is crucial to using big bang nucleosynthesis to set a limit on the number of families of light neutrinos[1,2]. However, to achieve significant improvements over the current, apparently satisfactory agreement between predictions of the standard hot big bang model and the observed primordial abundance (mass fraction) of helium, Y_P must be determined to precisions of $\leq 2\%$[2]! This extremely difficult observational requirement can most likely be achieved by improving measurements of Y in HII regions located in galaxies with low heavy element abundances ("metals")[3,4,5]. The advantage of this approach is that Y can be determined with reasonable precision in high excitation HII regions, while low "metals" suggest that the degree of contamination by elements synthesized in stars, including helium, will be minimal. A question, however, remains as to which heavy elements or combinations thereof are coproduced with helium and are therefore best suited as the tools for extrapolation to the cosmic ^{4}He abundance.

Most investigations of ^{4}He in low metallicity galaxies have used oxygen to trace levels of stellar contamination. However, these studies seem to show large intrinsic scatter in the relationship between oxygen and ^{4}He abundances in low metallicity galaxies. We will argue that this scatter may be due to the fact that oxygen comes almost exclusively from very massive ($M \geq 12 M_\odot$) stars whereas helium is also produced in significant amounts by low mass stars[6,7,8]. The purpose of this *Comment* will be to extend our earlier discussion[41] of the helium-heavy element relationships to make the first steps towards developing an optimum strategy for deriving primordial ^{4}He abundances from observations of nearby galaxies.

Currently studies of extragalactic HII regions yield Y values with estimated accuracies of better than 10% in the best cases[9,10,11,12]. A number of theoretical and observational obstacles must be surmounted to increase the precision with which Y_P is known to the 2% level. For example, intepretation of HII region emission line spectra in terms of element abundances is sensitive to the structure of the HII region[10,11,13], as well as to local physical processes, such as the role of collisional excitation in producing the nebular He I spectrum[14,15].

The experimental and intepretive problems surrounding measurements of Y in HII regions are most readily dealt with by observing HII regions in nearby galaxies. In these systems HII regions can be spatially resolved, which is helpful in improving the accuracy of fits to nebular models[16], high signal-to noise data are most easily obtained, and other HII region structural features, such as the nature of the stars responsible for ionizing the nebula, are directly discernable. Often it is also feasible to observe several HII regions within the same galaxy, which allows the estimated precison of the derived Y_P to be empirically tested.

Unfortunately, with the possible exception of the extreme dwarf galaxy GR8[17], all nearby galaxies have moderate levels of contamination by stellar nucleosynthesis products, at least as judged by their HII region ^{16}O abundances. Thus in those galaxies where the best data can be collected, model-dependent corrections for stellar contributions to the observed nebular Y could be significant; i.e. are estimated to be $\geq 10\%$. For this reason most recent work in this field has emphasized the search for very oxygen-poor HII galaxies where the stellar correction factor ΔY would be negligibly small[9,12]. But this approach has achieved only limited success since very low metallicity HII region galaxies turn out to be extremely rare in the local universe[12,18]; even the lower abundance bound set by I Zw 18 is now being questioned[19]. Furthermore, for this approach to work, one must assume that low oxygen abundances imply low stellar contamination levels of ^{4}He, but as mentioned before helium and oxygen do not necessarily come from the same stars.

2. EMPIRICAL ESTIMATES OF ΔY IN HII REGIONS

The most widely used method for finding a ΔY correction for stellar produced ^{4}He is based on the simple chemical evolution model of Peimbert and Torres-Peimbert[20,21], who parameterized Y linearly in terms of a mean metallicity level Z,

$$Y = Y_P + Z(\Delta Y/\Delta Z). \tag{1}$$

By measuring $Y(Z)$ over a range in Z, the slope $\Delta Y/\Delta Z$ can be estimated and the linear relationship extrapolated to $Z = 0$ yielding Y_P [22].

In practice Z is not measured, rather the mean metallicity is replaced with Z based on ^{16}O, since this is the most abundant metal whose abundance can be accurately measured in HII regions. When applied to systems having HII regions with abundances in the range $0.1 \leq (Z(^{16}O)/Z(^{16}O)_{\odot}) \leq 1$, the linear model has given good agreement with the data[19]. This suggests that $Y_P = 0.23$ and that more sophisticated chemical evolution models were not warranted by the data.

A controversy, however, has developed regarding the proper value of $\Delta Y/\Delta Z$. Theoretically this ratio depends sensitively on the structure of massive stars, since ^{16}O is produced only by stars with initial masses larger than about 12 $M\odot$, and on the form of the stellar initial mass function as a major contribution to ^{4}He comes from stars with initial masses of 5 $M\odot$ or less[23]. The disparity in stellar masses producing ^{16}O and ^{4}He makes $\Delta Y/\Delta Z(^{16}O)$ a highly leveraged quantity that depends on details of galactic chemical evolutionary histories. In particular, the rapid evolution of the oxygen producing stars can yield oxygen enrichment without substantial helium enrichment; e.g self contamination of the very HII regions where abundances are measured. Thus $\Delta Y/\Delta Z(^{16}O)$ would be expected to change as $\Delta(O/H) \rightarrow 0$ [24].

This idea, that $\Delta Y/\Delta Z$ varies with O/H, is supported observationally by the work of Kunth and Sargent[9]. They found results consistent with $\Delta Y/\Delta Z(^{16}O) \approx 0$ for oxygen abundances below a few tenths of solar, in contrast with $\Delta Y/\Delta Z(^{16}O)$ values of near 3 that are observed at higher metallicity levels[22] and theoretical predictions[7] that this ratio should be ≤ 1. Extrapolations from the measured Y values to the desired Y_P based on a linear model for the higher O/H points may overshoot as $O/H \rightarrow 0$ and yield too low a value for Y_P.

A need now exists for more sophisticated treatments of the relationship between ΔY and metallicity. Such models have been discussed in the literature, e.g. by Serrano and Peimbert[23]; so this is not a new idea. However, the observational hints that the expected Z dependence of $\Delta Y/\Delta Z$ is being seen and the possibility that ΔY is more closely correlated with ^{14}N or ^{12}C abundances than with $Z(^{16}O)$ [12,25,26] suggest that the issue of galactic chemical evolution models be reopened. The fundamental discovery by Lequeux et al.[27] that the oxygen abundance is closely linked to galactic mass in irregular galaxies, which has recently been reconfirmed[17,28,29], demonstrates the further possibility that abundances are influenced by factors other than stellar nucleosynthesis yields.

Given these complications, it is not yet established that we know how to predict the ΔYs in moderate-to-low metallicty galaxies to the precisions needed to sharpen tests of the standard hot big bang model. In the remainder of this comment we survey stellar heavy element yields and galactic chemical evolution considerations which allow us to assess roughly how well we might do if more complex models were applied to this problem.

3. STELLAR HELIUM PRODUCTION

Although precise stellar yields for ^{4}He are still lacking, *all* stars with initial masses of $M \geq 2M_\odot$ eject significant amounts of newly synthesized ^{4}He[7,8]. For example, if the yield of stellar ^{4}He is integrated over a Salpeter stellar initial mass distribution, then comparable fractions of the total yield are contributed by high and intermediate mass stars. No other primary species is synthesized over such a range in initial stellar mass and as a result no *single* element can be expected to track exactly stellar ^{4}He production. In particular, ^{16}O is made only by massive stars and therefore cannot tell us directly about helium production by intermediate mass stars. Carbon is thought to come primarily from intermediate mass stars (as is primary nitrogen[30,31]); so it may correlate better than oxygen with stellar ^{4}He production[8,32]. The problem with the use of carbon as an enrichment indicator is that HII region carbon abundances are much more difficult to measure than HII region oxygen abundances; thus the carbon abundance data are not yet as complete.

If only a single element is available to trace ^{4}He production in gas-rich, chemically unevolved galaxies, then one made in an intermediate mass star should be a better choice than one made in a massive star, but it is safer to use more than one metal abundance to estimate ΔY. One approach is to adopt ^{16}O as an estimator of massive star metal production, and then to add elements which are indicative of pollution levels of products of intermediate mass stars. As mentioned above, ^{12}C in principle can satisfy this condition. Nitrogen could also play this role, as its abundance is readily measured in HII regions, although it has the disadvantage that the astrophysical sites for ^{14}N synthesis are not well understood theoretically. An additional complication for carbon is the possibility that a variable fraction of this element could be locked up in grains and therefore missed in gas phase abundance determinations.

Pagel and coworkers[12] have already shown that ^{14}N and Y are correlated even in low metallicity galaxies. Measurements of ^{12}C abundances are less available and less accurate than those for ^{14}N, since ^{12}C gas abundances depend upon ultraviolet spectrophotometric observations[26,33,34]. In Figure 1 we show a plot of Y versus ^{12}C and ^{16}O abundances for several moderate-to-low metallicity extragalactic HII regions. We have chosen to normalize abundances to the solar values so as to show clearly the quality of linear fits. The resulting best fits are

$$Y = 0.230 \pm 0.001 + 0.048 \pm 0.006(O/O_\odot), \tag{2a}$$

$$Y = 0.231 \pm 0.001 + 0.096 \pm 0.015(C/C_\odot). \tag{2b}$$

In principle a first order improvement to the simple linear parameteriztion can be obtained by taking $Y = Y_p + A(C/C_{\odot}) + B(O/O_{\odot})$, although with presently available data, this does not yield a significantly better fit to the observations.

$$Y = 0.231 \pm 0.001 + 0.041 \pm 0.035(C/C_{\odot}) + 0.029 \pm 0.017(O/O_{\odot}) \quad (3)$$

An examination of the data and linear fits shown in Figure 1 should convince the reader that the formal error estimates are very optimistic. We conclude from Figure 1 that a reasonable estimate is $Y_P = 0.230 \pm 0.015$ if linear extrapolations of abundance patterns hold into the ultra-low metallicity regime.

A second factor related to stellar mass can also influence element abundances in small galaxies. Massive stars are often formed in groups where Type II supernova shells may overlap and produce "galactic chimneys" which can carry metal rich material out of the disk and even out of the galaxy[35]. Selective loss of metal-enriched Type II supernova ejecta has long been suspected to be an important factor leading to the existence of a mass-metallicity correlation among dwarf galaxies.

Loss of newly produced metals occurs when superbubbles break out of the galactic disk. Theoretical models and observations of holes in cool gas disks both suggest that this process will only occur for about 10-30 million years after a rich association of OB stars is formed[36]. Thus while the ejecta of Type II will be selectively lost in systems with low escape velocities, this mechanism will have less effect on those products of longer-lived intermediate mass stars or of binary, Type I supernovae. The point is that when the interval between supernovae in a region of a galactic disk becomes long, shells do not readily overlap and form chimneys. Elements, such as ^{12}C and ^{4}He, which are ejected at low velocities from asymptotic giant branch stars are even less likely to be preferentially lost from a small galaxy.

Flows out from (and into) galaxies can therefore influence metallicities in ways that are not included in the simple model used to predict ΔY. These arguments also suggest that it is indeed possible to make small galaxies with very low oxygen abundances but significant stellar helium contamination. But we see that by including metals produced in intermediate mass stars it should be possible to detect this effect and to calculate appropriate ΔY values from these elements. If this model for the mass-oxygen abundance correlation in dwarf irregular galaxies is correct, then weighting towards the intermediate mass star ΔY_{IMS} derived from ^{12}C and ^{14}N may give a better derived Y_P than using ΔY_{HMS} from ^{16}O.

An additional complication arises since oxygen and nitrogen can be produced by OB stars within HII regions. Such local self-contamination would lead to HII region abundances that are above the galactic mean. Kunth and Sargent[18] suggest that this process accounts for the lack of extremely metal-poor HII regions. Pagel[25] similarly notes that nitrogen abundances have the advantage of allowing one to trace local contamination by Wolf-Rayet stars within HII regions, a supposition that is supported by recent observations of nitrogen abundance variations *within* HII regions[37]. The same stars are likely to synthesize ^{4}He and thus it is unclear what correction should be applied to transform the observed HII Y into Y_P.

Finally we also need to consider effects of rapid time variations in galactic star formation rates, as are proposed in starburts models. Tinsley[38] demonstrated that production of material from lower mass stars, such as helium, will lag behind the rapidly-produced oxygen in a post-starburst galaxy. Similar effects can be seen in sophisticated galactic chemical evolution treatments of carbon[40], and in the suggestion for lagging nitrogen production by Edmunds and Pagel[39].

4. DISCUSSION

The observational data and theoretical understanding of chemical abundances in metal-poor extragalactic HII regions have advanced to the point where the use of a simple linear model to correct from observed to primordial ^{4}He abundances is no longer justified. We have no observational support for the hypothesis that $\Delta Y/\Delta Z(^{16}O)$ remains constant as $Z(^{16}O) \rightarrow 0$, and indeed we have reviewed a number of well known theoretical arguments that this condition is unlikely to hold under the complex conditions occurring in nature. The issues then are how to estimate the errors introduced by use of simple chemical evolution models and how to do a better job of matching models to observations.

We have proposed to extend the simple chemical evolution model by writing

$$Y = Y_P + AZ(^{16}O)(\Delta Y/\Delta Z(^{16}O)) + BZ(^{12}C)(\Delta Y/\Delta Z(^{12}C)). \quad (4)$$

If ^{14}N production sites were more clearly understood, then we could add a third term to this relationship (or, substitute ^{14}N for ^{12}C). In this way we may account more fully for the range of stellar masses which contribute to helium synthesis and thereby reduce our sensitivity to details of the form of the IMF, galactic evolution, and time dependence of the star formation process. For the idealized case in which equal amounts of stellar ^{4}He are contributed by high and intermediate mass stars, $A \approx B \approx 0.5$.

In practice it is currently difficult to obtain sufficiently accurate observations of ^{12}C abundances in HII regions to improve significantly on the accuracy of Y_P estimated by standard methods. Yet we should recognize that higher precisions are likely to be obtained in the future for Y in HII regions, and thus now is the time to begin planning the next generation of correction techniques to take us from observed Y to the desired Y_P with minimal model-dependent assumptions.

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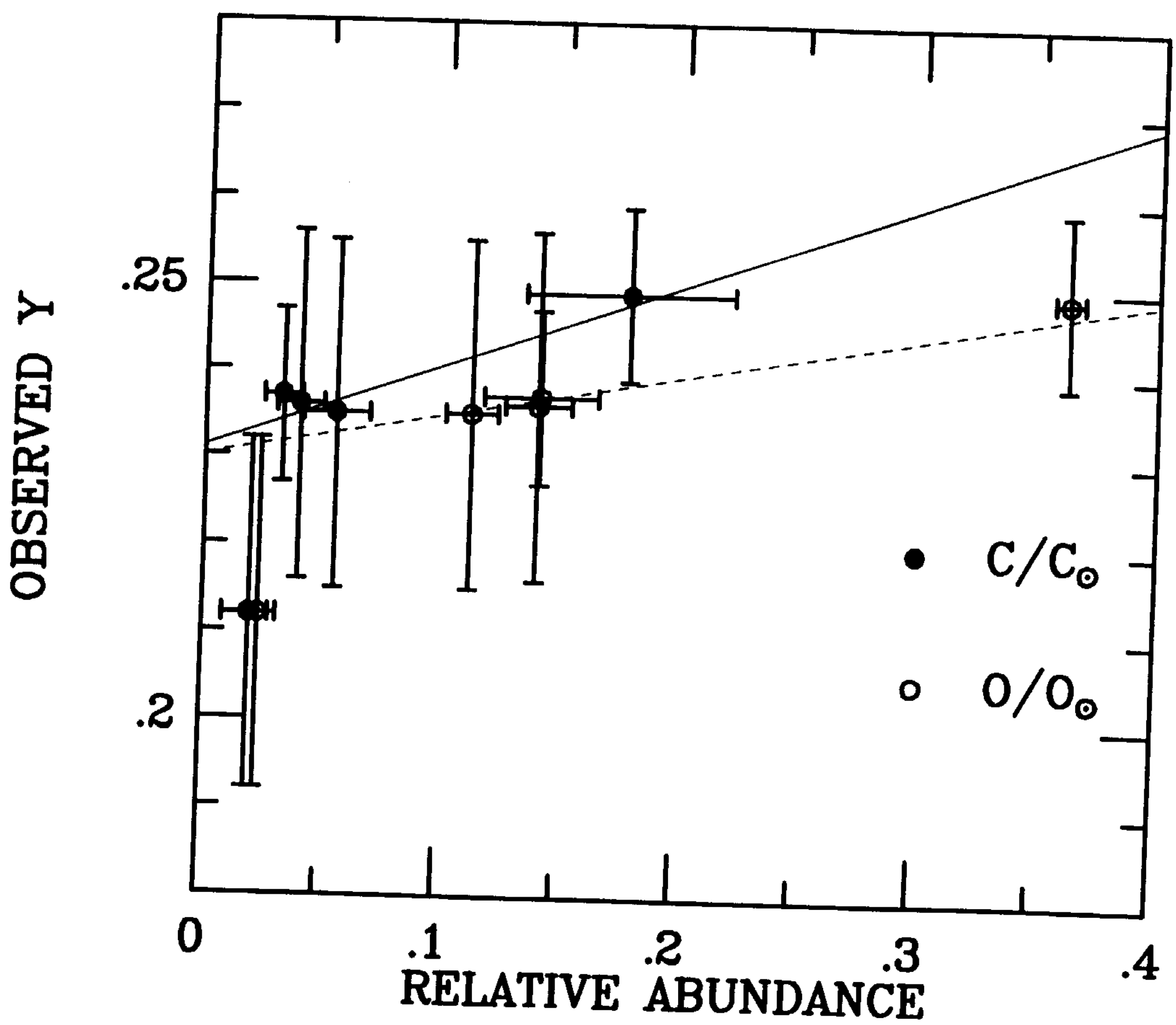
FIGURE CAPTION

FIGURE 1. This diagram shows observed helium abundances plotted against abundances of carbon and oxygen for HII regions located in metal-poor galaxies (LMC, SMC, NGC 2366, NGC 4861, I Zw 18). The solid line is the fit, eq. (2a), to the Y vs. O data; the dashed line is the fit, eq. (2b), to the Y vs. C data. The data are arbitrarily normalized to solar values for display convenience. Abundances have been taken from published values[10,11,20,21,26,34]. We have adopted generous error bars; e.g. to allow for the effects on abundances of recently recognized detector non-linearities. This plot is intended to be illustrative; we recommend reference to the original literature for a complete discussion of errors. See Pagel[25] for a similar plot for nitrogen.



OBSERVED Y
.25
.2
0
.1
.2
.3
.4
RELATIVE ABUNDANCE
C/C⊙
O/O⊙