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HELIUM IN HII REGIONS AND STARS

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Abstract: Following pioneering work in the 1960's and 70's, many efforts have been made to find the cosmologically and astrophysically significant parameters Y_p and dY/dZ as precisely as possible by observing emission lines in extragalactic HII regions. With the accumulation of improved data, several controversial issues have arisen and observational limits on Y_p and dY/dZ may have widened somewhat. New, accurate parallaxes from the HIPPARCOS satellite promise to revive interest in estimating Y_p and dY/dZ from main-sequence stars with differing metallicities, but even HIPPARCOS parallaxes will be marginal for fitting extreme subdwarfs.

1 Introduction and Historical Perspective

Helium is the second most abundant element in the visible universe and accordingly there is plenty of data from optical and radio emission lines in nebulae, optical emission lines in the solar chromosphere and prominences and absorption lines of hot stars. Yet more data are derived more indirectly by applying the theory of stellar structure, evolution and pulsation. Despite all this, there are still significant uncertainties in the important parameters Y_p and dY/dZ , partly owing to the high precision that is needed in order to derive significant results and partly because their determination involves extrapolations whose validity cannot be taken for granted.

Nevertheless, we have come a long way in the 40-odd years during which I have been aware of the subject and it is of some interest to take a look back at the early history (*cf.* Danziger 1970; Pagel 1982). In the 50's, there were conflicting estimates of the helium abundance in B-stars ranging from $y \equiv \text{He}/\text{H}$ by number of atoms ≈ 5 to $y \approx 15$ per cent, eventually settling down to somewhere near 10 per cent in agreement with preliminary estimates in the planetary nebula NGC 7027 by Menzel, Aller and Goldberg (*cf.* Aller 1956). In 1957, B²FII in their classic paper on stellar nucleosynthesis assumed for the most part that low-metallicity objects would also have low helium, but they wisely left open the possibility that there might be "some helium in the initial matter of the Galaxy" (Burbridge *et al.* 1957) and Burbridge (1958) noted the implications if

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the large amount of helium observed results from purely stellar production. Hoyle & Taylor (1964), in a remarkably prescient paper, pointed out the cosmological importance of the presence or absence of a universal "floor" to the helium abundance noting the dependence on the number of neutrino types (the ν_e had just been discovered) and Taylor in later papers pointed out also the significance of uncertainties in the neutron free-decay lifetime, which then was thought to be 1175s compared to the modern value of 889s (*cf.* Taylor 1990). Discovery of the microwave background in 1965 led to more detailed Big-Bang nucleosynthesis calculations (Peebles 1966; Wagoner, Fowler & Hoyle 1967, etc.) which in turn stimulated active searches for evidence for or against such a floor.

Investigations of line blanketing in the UVB colours (Eggen & Sandage 1962) initially suggested a very low helium abundance for low-metallicity subdwarfs, but Faulkner (1967) using a revised distance for the Hyades and more accurate quasi-homology relations showed that their data were more consistent with a primordial helium mass fraction $Y_p \geq 0.2$ and $\Delta Y/\Delta Z \approx 3.5$ resulting in a lower mass for globular cluster stars and an improved fit to their HIR diagrams (Faulkner & Iben 1966)*. Cayrel (1968) using colour systems less affected by blanketing also deduced a high helium abundance for cool subdwarfs. In the meantime, similarly high helium abundances in low-metallicity objects had been derived from the mass of the visual binary 85 Peg (Snak 1960), from the planetary nebula K-648 in the globular cluster M 15 (O'Dell, Peimbert & Kinman 1964) and from the blue edge of the RR Lyrae instability strip (Christy 1966).

About this time, attention was drawn to the lack of helium in the atmospheres of subdwarf B stars, on the blue extension of the horizontal branch (Sargent & Seale 1966; Greenstein & Münch 1966), and this caused much confusion until Sargent & Seale (1967) noted other chemical peculiarities reminiscent of chemically peculiar stars of Population I, supporting the explanation by gravitational settling (Greenstein, Truran & Cameron 1967; Catchpole, Pagel & Powell (1967), in an abundance analysis of μ Cas (an astrometric binary with a good parallax, but with a very faint secondary), used a mass estimate of $0.75 M_\odot$ for the primary by Wehniger & Wyckoff (1966) to derive (provisionally) a near-solar helium abundance in this mild subdwarf. Iben (1968) pointed out that the relative numbers of stars on the horizontal and red-giant branches of globular clusters provide robust evidence for a reasonably high initial helium abundance in those systems.

However, the controversy was not yet over. μ Cas figured once again in a report by Hegyi & Curott (1970) who deduced a large separation and hence a large mass and a low helium content from a tentative detection of the secondary using a photoelectric scanning system, and this paper (unlike ours!) attracted considerable attention. Faulkner (1971) pointed out serious mistakes and uncer-

* I thank John Faulkner for reminding me of the significance of his 1967 paper and for mentioning that his interest in the subject had been stimulated by his collaboration with Hoyle & Taylor.

tainties in their work* and there have been numerous investigations of μ Cas in the intervening years. The latest one, using speckle interferometry, gives a mass for the primary of $0.73 \pm 0.05 M_{\odot}$ and a helium mass fraction $Y = 0.23 \pm 0.05$ (Haywood, Hegyi & Gudehus 1992).

The controversy was finally settled, to all intents and purposes, when Searle & Sargent (1972) measured a near-normal helium abundance in the two famous Zwicky blue compact galaxies IZw18 and IIZw40, which they had identified as extragalactic HII regions with a very low heavy-element content (IZw18 still holds the record for low abundances in HII regions, with about 1/50 of the solar O/H ratio). Shortly afterwards, Peimbert and Torres-Peimbert (1974, 1976) used their accurate He/H determinations in the Magellanic Clouds and Orion to study the correlation between Y and the heavy-element mass-fraction Z (essentially proportional to O/H) and initiate a research programme to determine Y_p and the astrophysically significant parameter dY/dZ by plotting regressions of helium against oxygen in HII regions.

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;
B-stars	$< .28 \pm .05$	Prom. Hel	Heasley	ν problem
	$< .30 \pm .04$	Abs. lines	Kilian	Lev. pops.
				Precision
Subdw.	$.19 \pm .05$	ZAMS	Carney	$P_{\text{lx.}}$; T_{eff} ;
Glob-ular clusters	$.23 \pm .02$ $.20 \pm .03$ $.21 \pm .03$	RR, Δm $N(\text{HB})/N(\text{RG})$ HB in uv	Caputo Buzzoni Cole Bohlin	conv.
Gal. neb.	$.22 \pm .02$ $.22$	Plan. neb. HII regions	Peimbert Mezger	Physical basis of stellar evolution
Ex-gal. HII reg.	$.233 \pm .005$ $< .243 \pm .010$	Irr. + BCG BCG	Lequeux Kunth	enr. He ⁰ , enr. He ⁰ , data IIZw40

The ESO Workshop on "Primordial Helium" (Shaver, Kunth & Kjr 1983) collected together a variety of data from different sources. Table 1 gives a selec-

* He also pointed out that Wehinger and Wyckoff, whose mass estimate we had used, gave a wrong position angle. However, I have since been assured by Peter Wehinger that their separation measurement was a real one, even if they were not sure about the orientation of their telescope!

tion of results reported there, with some updating. The different objects give a quite consistent picture, but the best data come from emission lines in nebulae, especially extragalactic HII regions where low metallicites occur giving the twin advantages of hot ionizing stars (so that neutral helium is unimportant) and a short extrapolation to pregalactic abundances. The globular clusters and especially field subdwarfs can include still less processed material, but the errors due to uncertainties in the basic physics of stellar evolution are hard to quantify. Field subdwarfs have the additional problem of parallaxes, to which I return later.

Coming back to the extragalactic HII regions, there was some disagreement in 1983 between the results of Lequeux *et al.* (1979), who found a substantial slope $dY/dZ \simeq 3$ leading to an extrapolated $Y_p = 0.23$, and Kunth & Sargent (1983) who with generally better data but some bias due to the high weight given to $\lambda 5876$ in IIZw40 which is absorbed by Galactic sodium (French 1980), detected no slope and therefore presented only an upper limit to Y_p .

2 More Recent HII Region Studies

Having the good fortune to be working with Roberto and Elena Terlevich during the later 1980s, it seemed to me that their spectrophotometric survey of HII galaxies (Campbell, Terlevich & Melnick 1986; Terlevich *et al.* 1991) would be a good starting point for attempts to improve the situation on primordial and non-primordial helium. Davidson & Kinman (1985) had given a very careful survey of many of the difficulties involved, but I thought I had answers to most of them. Pagel, Terlevich & Melnick (1986) noted that there seemed to be real scatter in helium at a given oxygen abundance and we attributed this to local pollution by winds of hydrogen-burned material from embedded Wolf-Rayet stars that sometimes show up in the form of broad HeII λ 4686 and accordingly introduced the idea of plotting a regression against nitrogen as well as oxygen, in the vain hope that this effect would cancel out to first order. Later we added new data that we obtained with IPCS and CCD detectors using the INT and AAT; some (not enough) of this was of unprecedentedly good quality (especially AAT CCD data taken with a long-focus camera) and the results have been described in detail in Simonsen's thesis (1990) and in Pagel *et al.* (1992) where we combined our observations with selected (and, if necessary, corrected) data from the literature. The main problems in this and other work are listed below.

(i) Data quality and reddening corrections

Much effort was spent in checking the detector linearity and flux calibration, reddening being deduced in the usual way from the Balmer decrement. The reddening seriously affects only λ 5876, since λ 4471 and λ 6678 are close to Balmer lines, but the dynamic range is large, e.g. $\text{He}\alpha/\lambda$ 6678 $\simeq$ 100.

(ii) Theoretical recombination coefficients

In common with previous investigators we used coefficients calculated by Brocklehurst (1972), but later calculations by Smits (1991ab) show small though non-negligible differences. Smits (1994) vindicates Brocklehurst's values except

in the case of λ 7065 which is sensitive to radiative transfer and especially collisional effects.

(iii) He⁰ and underlying absorption lines

Neutral helium is not a problem if the ionizing stars are hot enough, which we were able to judge by comparing O⁺/O⁺⁺ and S⁺/S⁺⁺ ionization ratios. Weak [OII] lines implied that interference from a superposed low-ionization HII region would be insignificant. Underlying absorption lines can be a problem, especially for λ 4471, but could be safely neglected when the weaker λ 4388 line was seen. Because of underlying or intervening absorption effects, it is dangerous to use one helium line alone.

(iv) Radiative transfer and electron collision effects

Because of the metastability of the 2³S state, helium lines can be excited by fluorescence and electron collisions, as well as by pure recombination. Collisional effects were calculated from the electron density deduced from the [SII] line ratio using the formulae of Clegg (1987) and were very small, so we are not too worried by the suggestion that they are overestimated by up to a factor of 2 in planetary nebulae (Peimbert & Torres-Peimbert 1987). The agreement with λ 7065 seemed good enough to exclude significant fluorescence effects.

(v) Cosmic scatter in the He, O or He, N relation

There are some signs of a real dispersion in the helium abundance at a given “metallicity”. The evidence is marginal compared to possible errors, but it is interesting that Roelfsema, Goss & Mallik (1992) have found local helium excesses from radio observations of the Galactic HII region W3A. The most prominent case among our objects is that of NGC 5253, a nearby HII galaxy that is well resolved spatially and shows local variations in both nitrogen and helium abundance with a very narrow helium peak in the central nucleus which also shows a broad WR feature (Campbell, Terlevich & Melnick 1986). A correlation between excess helium and visible WR features is far from being proven, but in order to find an objective criterion for excluding such effects, we excluded all spectra showing a definite WR feature from our solutions. Fig 1 shows our results from Pagel *et al.* (1992) with some later data superposed.

The result from this was $Y_p = 0.228 \pm 0.005$ (s.e.), or, assuming a systematic error of up to 0.005, $Y_p \leq 0.242$ with 95 per cent confidence, and $dY/dZ = 4 \pm 1$ for O/H $\leq 2.4 \times 10^{-4}$ or 0.3 solar oxygen abundance, not significantly different from the results of Lequeux *et al.* (1979). We derived the same Y_p from the regression against nitrogen, taking into account the contribution of “secondary” nitrogen production, which led to some discussion but no serious subsequent change (Pagel & Kazlauskas 1993; Balbes, Boyd & Mathews 1993). The large dY/dZ , already implicit in earlier work (Faulkner 1967; Perrin *et al.* 1977; Lequeux *et al.* 1979), and supported by studies of planetary nebulae (Chiappini & Mactel 1994), has led to much discussion, since it is about twice the value expected from conventional stellar nucleosynthesis, and basically three different hypotheses have been put forward:

(i) A low upper limit ($\approx 25M_{\odot}$) to the initial mass of stars undergoing supernova explosions rather than going into black holes (Maeder 1992, 1993;

Fig. 1. Regressions of helium against oxygen and nitrogen in HII galaxies. Filled and open circles (representing objects respectively with and without definite WR features and with different sizes according to weight) are from Pagel *et al.* (1992); full and broken lines show their maximum-likelihood regressions and equivalent $\pm 1\sigma$ error limits. (The lines show their maximum-likelihood regressions and equivalent $\pm 1\sigma$ error limits. (The short line in the lower panel is the regression preferred for nitrogen, since there is some indication of a flattening at higher abundances.) The stars represent SBS 0335-052 recalculated from data by Melnick *et al.* (1992), while triangles show I Zw 18 from Skillman & Kennicutt (1993) and UGC 4483 from Skillman *et al.* (1994) and Izotov *et al.* (1994).

Brown & Beeth (1994). Apart from questions about the initial mass function and resulting absolute yields assumed by Maeder, objections have been raised by Prantzos (1994) on grounds of overproduction of carbon.

(ii) Preferential loss of oxygen and other components of Z by selective galactic winds following bursts of star formation in dwarf galaxies (Pilyugin 1993; Marconi, Matteucci & Tosi 1994). Pilyugin also includes temporary increases of both Y and Z by self-pollution of HII regions, for which Kunth *et al.* (1994) have provided independent evidence in the case of I Zw 18 from HST observations giving an extremely low oxygen abundance in the neutral gas. Such differences cannot, however, be a major factor in objects like the Magellanic Clouds and the Galaxy, where no HII regions are found to be overabundant relative to the

stellar population or the neutral gas, and the scatter in helium abundance that they are supposed to explain only marginally exceeds experimental errors.

(iii) Our oxygen abundances are underestimated because we assumed a uniform electron temperature. This seemed to be the right thing to do in 1992, but recently evidence has been found from recombination lines and Balmer and Paschen discontinuities in planetary nebulae, Galactic HII regions and even a low-abundance extragalactic HII region that our abundances could be too low by as much as a factor of 2 (González Delgado *et al.* 1995). For Galactic HII regions, with a generous allowance for temperature fluctuations ($t^2 = 0.04$), Peimbert (1993) has derived $\Delta Y/\Delta Z = 3.2$ for Orion, 3.5 for M8 and 2.5 for M17. An upper IMF slope of 1.7 and an upper mass limit of $50M_{\odot}$ for SN progenitors gives $\Delta Y/\Delta Z = 3$ (Maeder 1992), so this may be the solution.

3 Still More Recent HII Region Studies

At present, efforts are being made towards still further refinements of helium abundance determinations, concentrating on improvements in the following areas: Discovery of more low-metallicity systems (i.e. more low-luminosity galaxies), better signal:noise and resolution using various telescopes and calibration routines, and improvements in atomic data.

Skillman & Kennicutt (1993) have re-observed I Zw 18 and their result is shown in Fig 1, together with the result for UGC 4483 by Skillman *et al.* (1994) who used spectra taken at McDonald Observatory, the MMT, and the INT and WHT on La Palma. Further results from this group (Skillman *et al.* 1994ab) have been exhaustively analyzed, together with our data (Pagel *et al.* 1992), by Olive & Steigman (1994); from various subsets of the data, including most of the definite WR objects which we excluded, they find $Y_P = 0.232 \pm 0.003$ and $Y_P^{\text{2}\sigma} + \sigma_{\text{stat}} \leq 0.243$.

Izotov, Thuan & Lipovetsky (1994) have observed and analysed ten HII galaxies from the Second Byurakan Survey, using the 4m Mayall Telescope on Kitt Peak. They compare results using recombination coefficients by Brocklehurst (1972), Smits (1991ab) and Smits (1994), resulting in some confusion, since Smits (1994) confirms Brocklehurst (and so outdates Smits 1991) except in the case of λ 7065. Using Brocklehurst coefficients, they argue that the [SII] electron densities used by the rest of us are inappropriate for He⁺ and derive much higher densities from λ 7065 and accordingly larger corrections for collisions; but when this exercise is repeated with Smits (1994) coefficients, they find low electron densities that are actually in fair agreement with the ones from [SII]. Using Smits (1994) recombination coefficients and omitting one deviant galaxy, they find $Y_P = 0.239 \pm 0.007^*$ and $dY/dZ = 5.8^{\dagger} \pm 4.4$, the large error in dY/dZ

* With Brocklehurst coefficients the agreement with Pagel *et al.* is very much better, but, as they themselves remark, this is probably just fortuitous.

† With the corrections applied by Pagel *et al.*, this raw value is reduced to about 4.

coming from the rather small range in oxygen abundances among their objects. The Y_P value derived by Olive & Steigman is within 1σ of both Pagel *et al.* and Izotov *et al.*, but radiative transfer effects not previously taken into account could apparently raise the upper limit, perhaps by as much as 0.01 (Sasselov & Goldwirth 1994).

4 Location of Stars on the Main Sequence

HII regions provide the most accurate helium abundances, but it is useful to check them independently from considerations of stellar structure. Some results from globular clusters were briefly quoted in Table 1, and here I just comment further on studies of the main sequence as a function of metallicity.

The zero-age main sequence follows approximately quasi-homology relations of the form

$$L = (X + 0.4)^a (Z + Z_0)^b f(T_{\text{eff}}) \quad (1)$$

(cf. Faulkner 1967), where the first factor represents the molecular weight and the second the combined effect of opacity and nuclear energy generation, while $f(T_{\text{eff}}) \propto T_{\text{eff}}^7$, approximately. Models for low-metallicity stars aged 15 Gyr and with $\log T_{\text{eff}} = 3.72$ (e.g. Vandenberg 1983) fit this relation with $a \simeq 2.67$, $Z_0 \simeq 0.003$, $b \simeq 0.64$. As a result of this type of relation, correlated changes in helium and heavy-element abundances push the main sequence in opposite directions and tend to cancel each other out at the higher metallicities where, however, uncertainties in opacity, convection theory and corrections for evolution introduce major uncertainties. Perrin *et al.* (1977) were unable to find any metallicity-correlated dispersion among disk stars and from this with the aid of evolutionary tracks by Hejlesen they deduced $\Delta Y/\Delta Z = 5 \pm 3$ (see also Cayrel de Strobel in this volume), which looks like a fair estimation of the uncertainties, and their result gives modest support to the HII region data.

Carney (1983) used modified Yale isochrones to estimate the helium abundance in extreme subdwarfs, noting the difficulties that arise from systematic effects in the evolutionary tracks. Assuming that this problem can ultimately be solved, one can differentiate eq (1) to derive an error budget for the helium abundance:

$$\delta Y \simeq 0.44 \frac{\delta L}{L} + 3.1 \frac{\delta T_{\text{eff}}}{T_{\text{eff}}} \quad (2)$$

Assuming $\delta T_{\text{eff}}/T_{\text{eff}} = 1$ per cent, even a perfect parallax gives an error in Y of 0.03. Among the stars used by Carney, ground-based parallaxes are accurate to 5 per cent (contributing 0.04 to δY) in only one case, that of Groombridge 1830, the next best being HD 25329 with $\delta L/L \simeq 0.2$. There is thus considerable interest in forthcoming parallaxes from HIPPARCOS, but, disappointingly, it turns out that even with the HIPPARCOS accuracy of 2 m-arc, $\delta L/L$ for the next best candidate with extreme metal deficiency is 10 per cent, contributing an error in Y of 0.04. HIPPARCOS will undoubtedly lead to enormous improvements in the search for fine structure in the main sequence of nearby stars belonging to

the thin and thick disks, but submilliarcsec precision is needed in order to study the main sequence of extreme subdwarfs; this may be attainable with HST, if the correction to absolute parallax can be established well enough, but must otherwise await still more advanced space missions (Kovalevsky 1995).

References

- Aller, L.H. 1956, *Gaseous Nebulae*, London: Chapman & Hall, p. 199.
- Balbes, M.J., Boyd, R.N. & Mathews, G.J. 1993, *Ap. J.*, **418**, 229.
- Bollin, R.C., Cornett, R.H., Hill, J.K., Smith, A.M. & Stecher, T.P. 1985, *Ap. J.*, **292**, 687.
- Brocklehurst, M. 1972, *M.N.R.A.S.*, **157**, 221.
- Brown, G.E. & Bellet, H.A. 1994, *Ap. J.*, **423**, 659.
- Burbidge, G.R. 1958, *Pub. Astr. Soc. Pacific*, **70**, 83.
- Burbidge, E.M., Burbidge, G.R., Fowler, W.A. & Hoyle, F. 1957, *Rev. Mod. Phys.*, **29**, 547.
- Buzoni, A., Fusi-Peccì, F., Buonanno, R. & Corsi, C.E. 1983, *Astr. Ap.*, **128**, 94.
- Campbell, A., Terlevich, R.J. & Melnick, J. 1986, *M.N.R.A.S.*, **223**, 811.
- Caputo, F., Martinez Roger, C. & Paez, E. 1987, *Astr. Ap.*, **183**, 228.
- Carney, B.W. 1983, in *Primordial Helium*, p. 179.
- Catchpole, R.M., Pagel, B.E.J. & Powell, A.L.T. 1967, *M. N.R.A.S.*, **136**, 403.
- Cayrel, R. 1968, *Ap. J.*, **151**, 997.
- Chiappini, C. & Maciel, W.J. 1994, *Astr. Ap.*, submitted.
- Christy, R.F. 1966, *Ann. Rev. Astr. Ap.*, **4**, 353.
- Clegg, R.E.S. 1987, *M.N.R.A.S.*, **229**, 31P.
- Cole, P.W., Demarque, P. & Green, E.M. 1983, in *Primordial Helium*, p. 235.
- Danziger, I.J. 1970, *Ann. Rev. Astr. Ap.*, **8**, 161.
- Davidson, K. & Kinnman, T.D. 1985, *Ap. J. Suppl.*, **58**, 321.
- Fegge, O.J. & Sandage, A.R. 1962, *Ap. J.*, **136**, 735.
- Faulkner, J. 1967, *Ap. J.*, **147**, 617.
- Faulkner, J. 1971, *Phys. Rev. Lett.*, **27**, 206.
- Faulkner, J. & Iben, I., Jr. 1966, *Ap. J.*, **144**, 995.
- French, H.B. 1980, *Ap. J.*, **240**, 41.
- González Delgado, R.M. et al. 1995, *Ap. J.*, in press.
- Greenstein, G.S., Tsuran, J.W. & Cameron, A.G.W. 1967, *Nature*, **213**, 871.
- Greenstein, J.L. & Münch, G. 1966, *Ap. J.*, **146**, 618.
- Haywood, J.W., Hegyi, D.J. & Gudehus, D.H. 1992, *Ap. J.*, **392**, 172.
- Heasley, J.N. & Milkey, R.W. 1978, *Ap. J.*, **221**, 677.
- Hegyi, D. & Curott, D. 1970, *Phys. Rev. Lett.*, **24**, 415.
- Hoyle, F. & Tayler, R.J. 1964, *Nature*, **203**, 1108.
- Iben, I., Jr. 1968, *Nature*, **220**, 143.
- Izotov, Y.I., Tsvann, T.X. & Lipovetsky, V.A. 1994, *Ap. J.*, in press.
- Kilian, J. 1992, *Astr. Ap.*, **262**, 171.
- Kovalevsky, J. (ed.) 1995, IAU Symp. 166: *Astronomical and Astrophysical Objects of Submilliarcsecond Astrometry*, to appear.
- Kunth, D., Lequeux, J., Sargent, W.L.W., & Vallefond, F. 1994, *Astr. Ap.*, **282**, 709.
- Kunth, D. & Sargent, W.L.W. 1983, *Ap. J.*, **273**, 81.
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- Lequeux, J., Peimbert, M., Rayo, J.F., Serrano, A. & Torres-Peimbert, S. 1979, *Astr. Ap.*, **80**, 155.
- Maeder, A. 1992, *Astr. Ap.*, **264**, 105.
- Maeder, A. 1993, *Astr. Ap.*, **268**, 833.
- Marconi, G., Matteucci, F. & Tosi, M. 1994, *M.N.R.A.S.*, in press.
- Melnick, J., Haydari-Malayeri, M. & Leisy, P. 1992, *Astr. Ap.*, **253**, 16.
- Mezger, P. & Wink, J.E. 1983, in *Primordial Helium*, p. 281.
- O'Dell, C.R., Peimbert, M. & Kinnman, T.D. 1964, *Ap. J.*, **140**, 119.
- Olive, K.A. & Steigman, G. 1994, Preprint, UMN-TH-1230/94, OSU-TA-6/94.
- Pagel, B.E.J. 1982, *Phil. Trans. R. Soc. London A*, **307**, 19.
- Pagel, B.E.J. & Kazlauskas, A. 1993, *M.N.R.A.S.*, **256**, 49P.
- Pagel, B.E.J., Simonson, E.A., Terlevich, R.J. & Edmunds, M.G. 1992, *M.N.R.A.S.*, **255**, 325.
- Pagel, B.E.J., Terlevich, R.J. & Melnick, J. 1986, *Pub. Astr. Soc. Pacific*, **98**, 1005.
- Peebles, P.J.E. 1966, *Ap. J.*, **146**, 542.
- Peimbert, M. 1983, in *Primordial Helium*, p. 267.
- Peimbert, M. 1993, *Rev. Mex. Astr. Astrofis.*, **27**, 9.
- Peimbert, M. & Torres-Peimbert, S. 1974, *Ap. J.*, **193**, 327.
- Peimbert, M. & Torres-Peimbert, S. 1976, *Ap. J.*, **203**, 581.
- Perrin, M.-N., Hejlesen, P.M., Cayrel de Strobel, G. & Cayrel, R. 1977, *Astr. Ap.*, **54**, 779.
- Pilyugin, L. 1993, *Astr. Ap.*, **277**, 42.
- Prantzos, N. 1994, *Astr. Ap.*, submitted.
- Rodriguez, P.R., Goss, W.M. & Malik, D.C.V. 1992, *Ap. J.*, **394**, 188.
- Sargent, W.L.W. & Searle, L. 1966, *Ap. J.*, **145**, 652.
- Sargent, W.L.W. & Searle, L. 1967, *Ap. J. Lett.*, **150**, L33.
- Sasselov, D. & Goldwirth, D. 1994, preprint.
- Searle, L. & Sargent, W.L.W. 1972, *Ap. J.*, **173**, 25.
- Shaver, P.S., Kunth, D. & Kjær, K. (eds.) 1983, *Primordial Helium*, ESO, Garching.
- Simonson, E.A. 1990, PhD Thesis, Sussex University.
- Stillman, E.D. & Kennicutt, R.C., Jr. 1993, *Ap. J.*, **411**, 655.
- Stillman, E.D., Terlevich, R.J., Kennicutt, R.C., Jr., Garnett, D.R. & Terlevich, F. 1994a, *Ap. J.*, in press; 1994b, in prep.
- Smak, J. 1960, *Acta Astr.*, **10**, 153.
- Smits, D.P. 1991a, *M.N.R.A.S.*, **248**, 193.
- Smits, D.P. 1991b, *M.N.R.A.S.*, **251**, 316.
- Smits, D.P. 1994, *M.N.R.A.S.*, in press.
- Tayler, R.J. 1990, *Q. J. R. A. S.*, **31**, 371.
- Terlevich, R.J., Melnick, J., Masgosa, J. & Moles, M. 1991, *Astr. Ap. Suppl.*, **91**, 285.
- Türk-Chièze, S. & Lopez, I. 1993, *Ap. J.*, **408**, 347.
- VandenBerg, D.A. 1983, *Ap. J. Suppl.*, **51**, 29.
- Wagoner, R.V., Fowler, W.A. & Hoyle, F. 1967, *Ap. J.*, **148**, 3.
- Welling, P.A. & Wyckoff, S. 1966, *Astr. J.*, **71**, 185.