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COLLISIONAL EFFECTS IN THE HELIUM TRIPLETS, AND THE PRIMORDIAL HELIUM ABUNDANCE

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ABSTRACT

Attention is drawn to some consequences of recent ab initio quantal calculations of the cross section for collisional excitation of level three of neutral helium from the metastable 2^3S state. For conditions appropriate for extragalactic H II regions, such as those used to determine the primordial helium abundance, collisions enhance the λ5876 and λ6678 lines used to deduce the He/H ratio by factors of the order of 5%–30%. Collisional excitation is relatively more important in these H II regions than in galactic H II regions because of the high electron temperatures associated with these metal-deficient objects. The effect of collisions is to cause the helium abundance to be overestimated by as much as 30%. The mean of a small sample of O-He deficient objects is a helium mass fraction of $Y \approx 0.207 \pm 0.016$. Three objects in the sample have helium mass fractions significantly below current big bang predictions.

Subject headings: abundances — atomic processes — cosmology — nebulae: planetary

I. INTRODUCTION

Big bang nucleosynthesis has rejuvenated interest in measurement of He/H in H II regions (Peimbert and Torres-Peimbert 1974; Lequeux *et al.* 1979; French 1980; Kunth and Sargent 1983; Davidson and Kinman 1985; Dinerstein and Shields 1986). The helium mass fraction Y for a few extremely metal-deficient nebulae, objects expected to be least contaminated by stellar nucleosynthesis, sets an upper limit to the amount of helium synthesized in the early universe. This is a parameter with implications for the "new physics" thought to influence the initial conditions (Boesgaard and Steigman 1985).

It is commonly thought that hydrogen and helium lines are formed by radiative recombination under the conditions found in galactic and extragalactic H II regions; if so, then ratios of helium to hydrogen lines are simply related to the He/H abundance ratio in a way which is almost independent of the physical conditions (see Osterbrock 1974, hereafter AGN). It has been known for some time that overpopulation of the metastable 2^3S state of He I can make collisional excitation important for some lines; for example, 2^2S–2^3P λ10830 is predominantly collisionally excited under most circumstances (AGN). It is commonly assumed that 2^3P–3^3D λ5876 and 2^1P–3^1D λ6678, lines used to measure the He^+ abundance, are formed by recombination, however.

Some time ago Cox and Daltabuit (1971) pointed out that collisional excitation of both λ5876 and 2^3P–4^3D λ4471 from 2^3S could be important; unfortunately the cross sections for these optically forbidden excitations were somewhat controversial; Peimbert and Torres-Peimbert (1971) and Barker (1978) suggested on empirical grounds, and Brocklehurst (1972) from both theoretical and empirical arguments, that the proper collision rate was roughly one-third that proposed by Cox and Daltabuit. Basically, these authors compared the intensity of λ5876 with either λ4471 or λ6678, a singlet arising from the decay of 3^1D. A comparison between the observed and predicted ratios (assuming pure recombination in the case of λ6678) sets a limit to any collisional contribution. This limit made the Cox-Daltabuit mechanism relatively unimportant in H II regions, because of their relatively low temperatures and electron densities.

Recently, Berrington *et al.* (1985) published the results of an 11 state R-matrix calculation; this work was the first ab initio calculation of the cross section and rate coefficient for the 2^3S–3^3D transition which should be the dominant channel contributing to collisional enhancement of λ5876. Their rate coefficient is roughly 2 times smaller than that deduced by Cox and Daltabuit for low temperatures (~ 5000 K), but asymptotically approaches the Cox and Daltabuit value for high temperatures (~ 20,000 K). The new rates for population of the 3^1D state giving rise to λ6678 are also significant, and this line is enhanced relative to recombination by a factor fairly similar (~ 50%) to the enhancement of λ5876. It is this similarity which invalidates previous upper limits to the importance of collisional excitation based on comparison to λ6678.

The purpose of this *Letter* is to draw attention to these rate coefficients and point out that λ6678 and λ5876 will be enhanced by up to 30% for conditions appropriate to the extragalactic H II regions used for studies of the primordial helium abundance. When the appropriate corrections are made, it is found that several objects have helium mass fractions below predictions of current models of the big bang. This result may challenge present ideas concerning nucleosynthesis in the early universe. We also note that the helium abundances of planetary nebulae have probably been overestimated by as much as 50%.

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II. THE HELIUM TRIPLETS

In this section we derive simple estimates of the importance of collisional excitation of λ5876 and λ6678. Comparisons with an unpublished 12 level atom calculation show that the corrections derived below are accurate to better than 3% for conditions appropriate to H II regions. Balancing radiative recombination to all the triplets with both exchange collisions to the singlets and the predominantly magnetic dipole 2^3S–1^1S decay, we find (see also AGN)

$$N(2^3S) = \frac{N_e N_{\mathrm{He}^+} \alpha_{\mathrm{tri}}(T_e)}{(N_e C_{\mathrm{exch}} + A_{31})}, \quad (1)$$

where

$$\alpha_{\mathrm{tri}}(T_e) = 2.04 \times 10^{-13} t_4^{-0.73} \mathrm{~cm}^3 \mathrm{~s}^{-1} \quad (2)$$

is the recombination coefficient, $t_4 = T_e/10^4$K, $A_{31} = 1.13 \times 10^{-4}$ s^{-1} is the spontaneous 2^3S–1^1S radiative rate (Drake 1971; Hata and Grant 1981), and N_e, N_{He^+}, and $N(2^3S)$, are the electron, singly ionized helium, and 2^3S state densities, respectively. The triplet → singlet exchange collision rate coefficient can be approximated as (Berrington *et al.* 1985)

$$C_{\mathrm{exch}}(T_e) = 3.33 \times 10^{-8} t_4^{0.21} \mathrm{~cm}^3 \mathrm{~s}^{-1} \quad (3)$$

over $1 \le t_4 \le 2$, the range of temperatures both encountered in H II regions and high enough for collisional excitation to be important. With these approximations, the relative population of 2^3S is

$$\frac{N(2^3S)}{N_{\mathrm{He}^+}} = \frac{6.13 \times 10^{-6} t_4^{-0.94}}{(1 + 3390 t_4^{-0.21} N_e^{-1})}. \quad (4)$$

The ratio of the rate for collisional excitation of λ5876 to its recombination rate is given by

$$\frac{I(\lambda 5876)_{\mathrm{coll}}}{I(\lambda 5876)_{\mathrm{rec}}} = \frac{N(2^3S) N_e C(2^3S, 3^3D)}{N(\mathrm{He}^+) N_e \alpha_{5876}^{\mathrm{eff}}} \times \frac{A(3^3D, 2^3P)}{[A(3^3D, 2^3P) + A(3^3D, 3^3P)]}, \quad (5)$$

where

$$C(2^3S, 3^3D) = 9.65 \times 10^{-8} t_4^{0.36} e^{-3.776/t_4} \mathrm{~cm}^3 \mathrm{~s}^{-1} \quad (6)$$

is the collisional excitation rate coefficient from Berrington *et al.* (1985),

$$\alpha_{5876}^{\mathrm{eff}} = 4.93 \times 10^{-14} t_4^{-1.14} \mathrm{~cm}^3 \mathrm{~s}^{-1} \quad (7)$$

is the effective recombination coefficient for λ5876 (Brocklehurst 1972; AGN), and the branching ratio strongly favors emission of λ5876 (Weise, Smith, and Glennon 1966). The ratio is then

$$\frac{I(\lambda 5876)_{\mathrm{coll}}}{I(\lambda 5876)_{\mathrm{rec}}} = \frac{12.0 t_4^{0.56} e^{-3.776/t_4}}{(1 + 3390 t_4^{-0.21}/N_e)}. \quad (8)$$

Approximating the rate coefficient for collisional excitation of 3^1D from 2^3S by

$$C(2^3S, 3^1D) = 1.34 \times 10^{-8} t^{-0.28} e^{-3.777/t_4} \mathrm{~cm}^3 \mathrm{~s}^{-1} \quad (9)$$

and the effective recombination coefficient by

$$\alpha_{6678}^{\mathrm{eff}} = 1.62 \times 10^{-14} t_4^{-1.16} \mathrm{~cm}^3 \mathrm{~s}^{-1}, \quad (10)$$

then the same ratio for λ6678 is

$$\frac{I(\lambda 6678)_{\mathrm{coll}}}{I(\lambda 6678)_{\mathrm{rec}}} = \frac{5.07 t^{-0.06} e^{-3.777/t_4}}{(1 + 3390 t_4^{-0.21}/N_e)}. \quad (11)$$

III. APPLICATION TO NEBULAE

Unfortunately, the collisional enhancements of He I lines are sensitive to both electron density and temperature. The temperature in the He^+ zone can be determined from the [O III] λ5007/λ4363 ratio, which model calculations show to be only slightly below $\langle T(\mathrm{He}^+)\rangle$. The electron density is more of a problem, since the only easily observed density-dependent ratios are produced by the np^3 ions O^+ and S^+, species found only near the H^+–H° ionization front, where the electron fraction is well below average; model calculations show that the N_e estimated by these ions can be a factor of 2 below the average in a constant hydrogen density model. The discrepancy will be even larger if there is a density gradient across the nebula. The density indicated by the [S II] ratio will be used in this discussion, with the understanding that the collision correction factor may be underestimated by more than a factor of 2. The helium abundances deduced below will be overestimates because of this.

Galactic nebulae can test whether the collisional terms considered above are reasonable. Peimbert and Torres-Peimbert (1971), Brocklehurst (1972), Barker (1978), and Davidson and Kinman (1985), among others, concluded that collisional effects on the triplets were fairly small. This conclusion was reached based on a comparison of the intensity of λ5876 with weaker lines, including λ6678, which Berrington *et al.*'s (1985) results show should also be enhanced by collisions, and λ4471, a line for which reliable collision strengths do not yet exist. The planetary nebula NGC 7027 has been very carefully studied (Kaler *et al.* 1976; Kaler 1976) and can be used to investigate collisional effects on lines arising from $n = 3$. Kaler *et al.* report an intensity ratio $I(\lambda 5876)/I(\lambda 6678)$ of 4.15 ± 0.24, after making corrections for reddening and blending of λ6678 with an underlying He II Pfund line. Brocklehurst (1972) finds a theoretical value of 3.49 for this ratio. Assuming $t = 1.15$, $N_e = 5 \times 10^4$ cm^{-3} (Kaler *et al.* 1976) and the expressions derived above, the predicted intensity ratio, including both recombination and collisions, becomes 4.32. (Note that the 6678/5876 ratio changed by only 24% while collisionals increased the emissivity of λ5876 by ~ 46%.) Berrington *et al.*'s (1985) rates are consistent with observations of NGC 7027.

Table 1 summarizes steps to the helium abundances of some extragalactic H II regions. The list is incomplete but was

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TABLE 1

HELIUM ABUNDANCES

Object	t (K/10^4)	N_e (cm^{-3})	y (5876)[a]	y' (5876)[b]	y (other)[c]	Y[d]	Reference
NGC 4861...........	1.40	100.	0.0794	0.0764	0.0	0.234	1
CG 1116+51	1.54	900.	0.0856	0.0613	0.0	0.197	1
I Zw 18	1.73	300.	0.063	0.054	0.003	0.186	2
II Zw 40.............	1.33	300.	0.0689	0.0644	0.002	0.209	3
	1.28	300.	0.065	0.0612	0.001	0.199	4
Tol 35................	1.24	250.	0.066	0.063	0.007	0.219	4

[a] Helium abundance, by number, indicated by λ5876 assuming pure recombination.

[b] Helium abundance, corrected for collisions.

[c] Abundance of neutral and doubly ionized helium, taken from the original references.

[d] Total helium mass fraction.

REFERENCES.—(1) Dinerstein and Shields 1986. (2) Davidson and Kinman 1985. (3) Lequeux *et al.* 1979. (4) Kunth and Sargent 1983.

chosen either because the object was well studied, or had especially low helium or oxygen abundances. Temperatures were taken from the original references. Densities are from the red [S II] doublet. Davidson and Kinman (1985) do not report a density, but do give [S II] λ6717/λ6731 = 1.19. This ratio was converted to density assuming their T_e, the radiative rates of Mendoza and Zeippen (1982), and the collision strengths of Mendoza (1983). The fourth column gives the He^+ abundance, by number relative to hydrogen, deduced from the λ5876 line alone assuming recombination only. Several authors also report observations of λ4471, for which reliable collision rates do not exist, but few observe λ6678. The next columns give the corrected (from eq. [8]) He^+ abundance, the abundance of other stages of ionization, from the original references, and finally the helium mass fraction. Two independent studies of II Zw 40 exist, and are reported separately. The mean of this (biased) sample is $Y = 0.207 \pm 0.016$. Excluding the high-helium object NGC 4861 the average has much less scatter and is $Y = 0.202 \pm 0.011$. The lowest values of Y predicted by standard big bang models are near $Y \approx 0.22$ (Boesgaard and Steigman 1985). Three objects in this sample have helium mass fractions significantly below big bang predictions.

IV. DISCUSSION

The purpose of this *Letter* is to draw attention to the importance of collisional effects on estimates of the primordial helium abundance. The determination of Y is an important question at the physics-astronomy interface, but one which requires great care and precision if the results are to be decisive (Davidson and Kinman 1985; Dinerstein and Shields 1986). Collisions introduce a systematic error; λ5876 and λ6678 are strengthened, and the helium abundance overestimated, by as much as 30%. It is not possible to neglect or "turn off" the physics predicted by Cox and Daltabuit (1971) and verified by Berrington *et al.* (1985); these effects must be included in measurements of Y. If anything, collisional effects have been underestimated here because of the use of electron densities indicated by the [S II] lines. These are produced near the hydrogen ionization front, a region not characteristic of the He^+ zone. Previous measurements of Y were already near the lower bound of conventional big bang predictions; the use of the proper emissivities lowers the helium abundance of three well-studied objects to values substantially below conventional big bang predictions. This result presents a challenge to present ideas concerning nucleosynthesis in the early universe.

The fact that Berrington *et al.*'s (1985) collision rates result in helium abundances at variance with big bang nucleosynthesis is certainly cause for concern. It is to be expected that the collision cross section for excitation to the $n = 3$ states will be lowered when higher states are included in the quantal calculation. The effect would be to lower the effective collision strengths for very high temperatures, but many of these excitations will eventually populate $n = 3$ as the excited electron cascades downward. The need for further calculations is obvious. It is important that the helium spectra of a few objects be very well observed to confirm the reliability of the calculations. Planetary nebulae are ideal candidates for such tests because of their higher density, temperature, and brightness. Collisions increase the emissivity of λ5876 by ~ 50% for conditions appropriate to typical planetaries. (Note that helium abundances of planetary nebulae have probably been overestimated by this factor.) Densities should be determined from ions which occur well inside the He^+ region; such np^3 ions as Ne^{+3} and Ar^{+3} may prove useful. Collisional rate coefficients do not now exist for principal quantum numbers greater than 3, so in order to test these predictions it will be necessary to compare lines arising from $n = 3$ to very weak lines coming from highly excited triplet states; the Boltzmann factor gives some assurance that collisional effects are not important and that recombination is the dominant excitation mechanism. Low lying singlet lines are not good candidates for this test because these states are also affected by collisions from 2^3S. High-n or moderate-n He I singlet lines also are not satisfactory because it seems unlikely that high-n Lyman lines scatter often enough for case B to apply (Ferland 1980). Such careful observations should receive high priority.

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