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PHOTOIONIZATION MODELS OF METAL-POOR EXTRAGALACTIC H II REGIONS AND THE PRIMORDIAL HELIUM ABUNDANCE

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RESUMEN

Discutimos el efecto de la contribución colisional a la intensidad de las líneas de Balmer en la determinación de la abundancia de helio primordial. Con este objetivo, presentamos un modelo de fotoionización de la región H II extragaláctica de baja metalicidad SBS 0335–052. Mostramos que la abundancia de helio (Y) derivada en esta región depende de la contribución colisional a las líneas de Balmer, tanto directa (a través de una subestimación del cociente He/H real) como indirectamente (a través de una sobreeestimación de la extinción interestelar). Desglosamos la forma en que ambos efectos afectan a la determinación de Y.

ABSTRACT

We discuss the effects of collisional enhancement of Balmer lines on the determination of the primordial helium abundance. To this aim, we present a photoionization model of the metal-poor extragalactic H II region SBS 0335–052. We show that the derived helium abundance (Y) of this H II region depends on the amount of collisional excitation affecting the Balmer lines, both directly (through an underestimation of the actual He/H ratio) and indirectly (through an overestimation of the interstellar reddening). We detail how each of these effects affects the derived value of Y.

Key Words: **GALAXIES: ABUNDANCES — GALAXIES: ISM — H II REGIONS — ISM: ABUNDANCES**

1. INTRODUCTION

This contribution highlights the difficulties of obtaining accurate determinations of the helium abundance (Y) in low-metallicity H II regions. High-quality Y values are necessary in order to reduce the uncertainty in the derived value of the primordial helium abundance (Y_P), which is a fundamental quantity in cosmology: see also the reviews by Luridiana(2003) and Peimbert (2003) for more complete discussions of this topic and a quantitative estimate of the error budget in the determination of Y_P.

One of the main contributors to the overall uncertainty in Y for individual regions is the collisional enhancement of Balmer lines. In H II regions, the main process contributing to the intensity of Balmer lines is H^+ recombination, but a further contribution can arise from the collisional excitation of H^0 from the ground state. This contribution is generally a minor one, but it might reach a value of several percent under appropriate conditions; since it depends both on the fraction of H^0 and on the temperature, its evaluation requires both these quantities to be known accurately.

To illustrate the difficulties inherent to this task and suggest possible solutions, we present a photoionization model of SBS 0335–052, an extremely low-metallicity extragalactic H II region, and show how the abundance analysis of this object should be modified to take into account the collisional enhancement. In a forthcoming paper Luridiana et al.(2003) we will present a more extended analysis of this object, as well as photoionization models of two other low-metallicity regions, H 29 and I Zw 18. See also Davidson & Kinman(1985), Skillman & Kennicutt(1993), Stasińska & Izotov(2001), and Peimbert et al.(2002) for previous discussions of this topic.

Low-metallicity regions are the most affected by collisions, since the collisional excitation of Balmer lines depends very steeply on temperature, which is especially high in these objects. As a rule of thumb, collisional contribution may be safely neglected in the analysis of objects with $T_e \lesssim 15,000$ K, while in hotter objects it may enhance the Hβ intensity by up to several percent. If not taken into account, this enhancement has two biasing effects on the determination of Y_P: first, if the observed intensity is interpreted in terms of pure H$^+$ recombination, the He$^+$/H$^+$ abundance is underestimated; second, since the percentual collisional increase in Hα is always higher than that in Hβ, the measured Hα/Hβ ratio is larger than it would be without collisions, producing a spurious reddening in the Balmer spectrum (Ferland & Osterbrock 1985). If this extra-reddening is mistaken for the effect of interstellar extinction, the dereddened ratios $I(\lambda)/I(\mathrm{H}\beta)$ derived for lines blueward of Hβ are overestimated, and those derived for lines redward of Hβ are underestimated. The net effect of such bias is a decrease of the derived Y value, since the helium lines redward of Hβ are globally brighter than those blueward of Hβ and weigh more in the abundance analysis. We will show this effect quantitatively in the case of SBS 0335–052, the second most metal-poor H II region known.

2. SBS 0335–052

SBS 0335–052 is a roundish region with a linear radius $R \sim 800$ pc. The reddening coefficient $C(\mathrm{H}\beta)$ determined by Izotov et al.(1999) varies from 0.225 to 0.33 along the slit; we will adopt in the following the value $C(\mathrm{H}\beta) = 0.25$, corresponding to the total $F(\mathrm{H}\alpha)/F(\mathrm{H}\beta)$ in the slit.

The model presented in this paper was computed with the photoionization code Cloudy 94 (Ferland(2000a,b); the ionizing source was computed with Starburst99 (Leitherer et al. 1999). We adopted the following input parameters: $Q(\mathrm{H}^0) = 2.2 \times 10^{53}$ s^{-1}; $Z_* = 0.0010$; $t = 3.2$ Myr; $Z_{gas} = 0.0007$; filling factor $\epsilon = 1.9 \times 10^{-3}$; covering factor $cf = 0.80$; and a Gaussian density law $N_\mathrm{e} = \max\left(N_\mathrm{e}^{\max}\exp(r/r_0)^{-2}, N_\mathrm{e}^{\min}\right)$, with $N_\mathrm{e}^{\max} = 600$ cm^{-3}, $N_\mathrm{e}^{\min} = 90$ cm^{-3}, and $r_0 = 225$ pc. The results will be compared against the observational data by Izotov et al.(1999). The model's output is presented both for the complete Strömgren sphere, and modified to take into account the aperture effect introduced by the $1'' \times 5.4''$ slit used by Izotov et al.(1999), which was divided into 9 extractions (Figure 1). The model's predictions will be presented in the following figures as a function of the radius of the structure, both in linear (parsec) and angular (arcsec) units; the bottom axis is in arcsec for those plots that simulate observational (projected) quantities, and in parsecs for those plots that describe theoretical (radial) quantities.

Figure 2 shows the profiles of the principal emission lines predicted by our model. The theoretical points correspond to the simulation of the nine extractions making up the slit; they are compared to the intensities observed by Izotov et al.(1999).

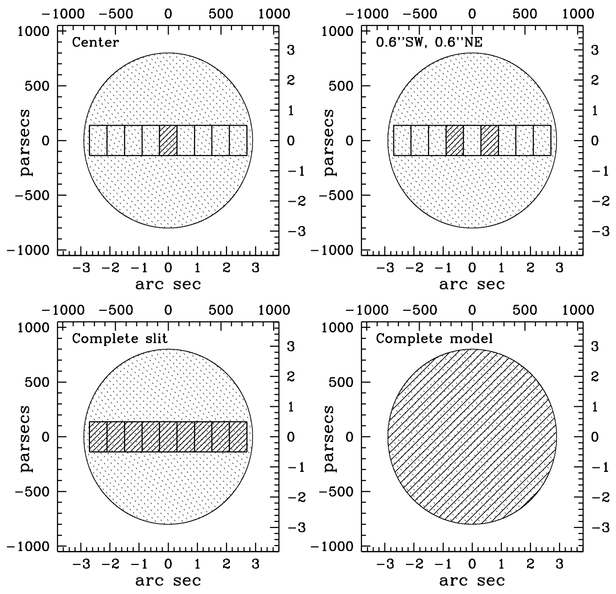

Fig. 1. Sketch of the slit used by Izotov et al.(1999), and the nine extractions making it up, projected onto the model nebula (see text). The assumed distance is $d = 57$ Mpc.

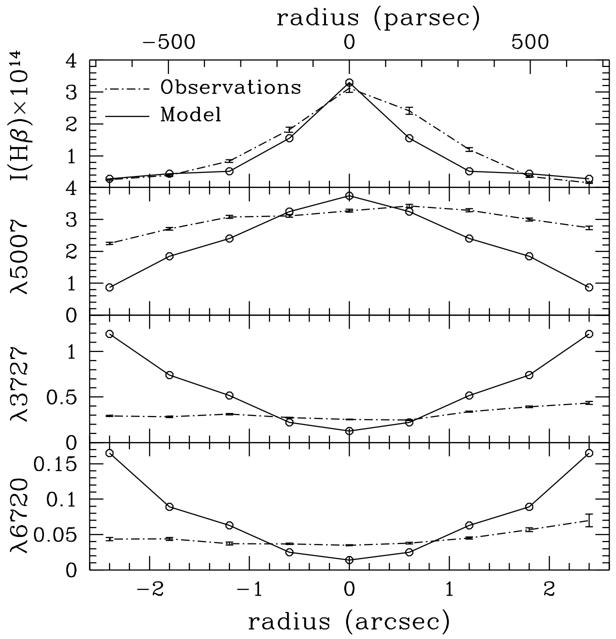

Fig. 2. Predicted profile of some emission lines (solid line) compared to the observational data (dot-dashed line).

Figure 3 shows the radial (theoretical) behavior of various quantities related to the collisional contribution: from the top down, the ratio between the

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collisional and the recombination emissivities of Hα and Hβ; the differential contribution of the collisional and the recombination process to the Hα and Hβ luminosities; the cumulative collisional and recombination Hα and Hβ luminosities; the hydrogen ionization structure; and, in the bottom panel, the electronic temperature and density. The top panel of Figure 4 compares the projected profiles of the Hα and Hβ luminosities, with the aperture effect taken into account; the bottom panel of the same figure compares the predicted profile of the total Hα/Hβ ratio to the profile of the Hα/Hβ ratio that would result from pure recombination. The recombination profile is almost constant, as expected from recombination theory for a structure with a fairly constant temperature profile; however, the collisional contribution, which peaks around $R \sim 700$ pc as a result of the interplay between the temperature and the H^0 fraction (Figure 2), increases the total Hα/Hβ ratio along the whole diameter, and particularly in the outermost extraction (which is centered on $R \sim 600$ pc).

This increase in the total Hα/Hβ ratio would be observationally undistinguishable from an increase due to interstellar extinction: in Figure 5 we give examples of the reddening coefficient which would be observed along the nebula for various assumptions on the true extinction coefficient $C(\mathrm{H}\beta)^{\mathrm{true}}$.

3. EFFECTS OF COLLISIONS ON THE DETERMINATION OF Y

Table 1 presents the values of some helium line fluxes, along with three sets of reddening-corrected line intensities. In the first set we neglect the collisional effects in the hydrogen lines; in the second we subtract the collisional contribution from the observed $I(\mathrm{H}\beta)$, but we neglect the collisional effects on the observed reddening; finally, in the third we subtract the collisional contribution from both $I(\mathrm{H}\beta)$ and $C(\mathrm{H}\beta)^{\mathrm{obs}}$. The $C(\mathrm{H}\beta)$ values associated to each intensity set are also listed. The table also presents the resulting y^+ values, and the difference in the derived helium abundance ΔY for each of the three cases; these numbers are based on a very simple analysis, and are meant to provide only a rough indication of collisional effects. A more sophisticated analysis, based on better models and on an improved algorithm for abundance analysis, will be presented in Luridiana et al.(2003).

The following facts should be considered when reading this table: first, the effect depends on the number of lines used; second, the lines redward of Hβ are more brilliant, and therefore dominate the

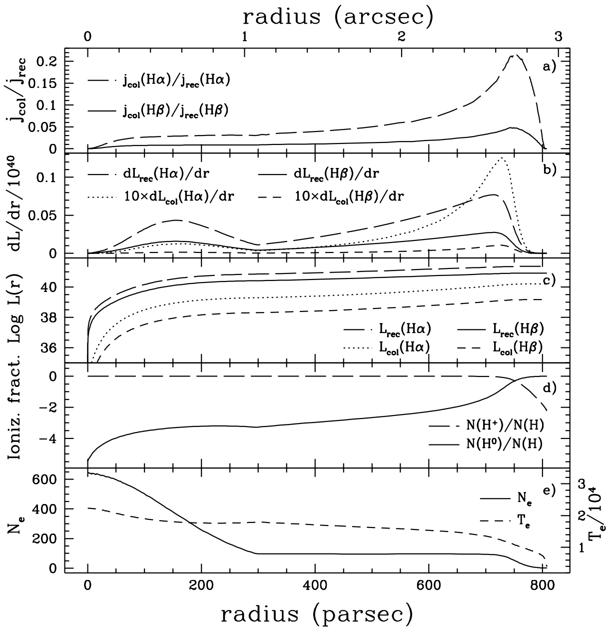

Fig. 3. Predicted radial behavior of several quantities related to collisional enhancement: a) ratio between the collisional and the recombination emissivities of Hα and Hβ; b) differential contribution of the collisional and the recombination process to the Hα and Hβ luminosities; c) cumulative collisional and recombination Hα and Hβ luminosities; d) hydrogen ionization structure; e) electronic temperature and density.

abundance determination; third, the effect might be a strong function of the position, especially in real nebulae, in which the behavior of the temperature and ionization degree are much less smooth than in a model.

4. SUMMARY AND CONCLUSIONS

In this work we discuss the influence of collisional enhancement of hydrogen lines on the accuracy of Y_P determinations. The final goal of this project, which is presented in its entirety in Luridiana et al.(2003), is to quantify the correction that should be applied to previous Y_P determinations in which collisional enhancement of Balmer lines has been neglected, and to estimate the uncertainty attached to such correction. In this framework, we also investigate to which extent the predicted collisions are model-dependent, and note that the occurrence of temperature fluctuations in real regions would enhance the collisions with respect to predicted values.

We show that the helium abundance in individual objects may have been underestimated as a consequence of the Hβ collisional enhancement. The underestimation in the Y values arises from the combination of two factors: the collisional Hβ enhance-

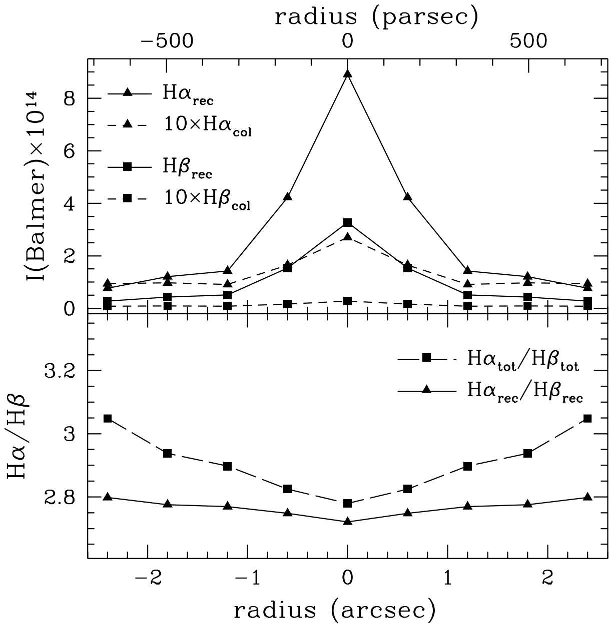

Fig. 4. Top: projected profiles of the Hα and Hβ luminosities, with the aperture effect taken into account; bottom: comparison between the predicted profile of the total Hα/Hβ ratio and the profile of the Hα/Hβ ratio that would results from pure recombination.

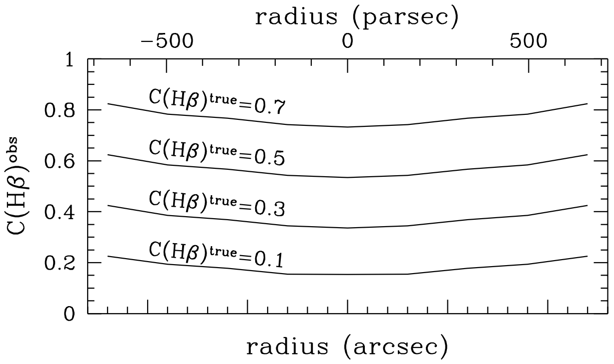

Fig. 5. Predicted reddening coefficient along the model nebula for various assumption on the true extinction coefficient $C(\mathrm{H}\beta)_{\mathrm{real}}$.

ment and the collisional reddening. Since the last factor mimics a higher $C(\mathrm{H}\beta)$, the quantitative effect of the collisional bias on Y_P is a function of the He I lines used in the analysis.

As a consequence of this bias, the Y_P value has also been underestimated. Since the effect on the individual Y values is more pronounced at high electronic temperatures, which characterize low-metallicity objects, the net effect on the $Y-Z$ relation is a decrease of the slope.

TABLE 1

HELIUM LINE INTENSITIES AND ABUNDANCES[a]

λ	$\frac{F(\lambda)}{F(\mathrm{H}\beta)}$	$\frac{I(\lambda)}{I_{tot}(\mathrm{H}\beta)}$	$\frac{I(\lambda)}{I_{rec}(\mathrm{H}\beta)}$	$\frac{I(\lambda)}{I_{rec}(\mathrm{H}\beta)}$
4026	1.294	1.473	1.490	1.461
4471	3.404	3.616	3.659	3.626
4921	0.821	0.816	0.825	0.826
5876	11.476	10.169	10.290	10.477
6678	3.237	2.631	2.662	2.746
Hα	3.339			
$C(\mathrm{H}\beta)$		0.25	0.25	0.21
$\langle y^+\rangle$		0.0825	0.0835	0.0846
ΔY		0.0000	0.0023	0.0047

[a]Observed He I line fluxes, relative to Hβ, and corresponding dereddened intensities for three different assumptions on collisional effects (see Section 3).

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