Carbon and Oxygen Galactic Gradients: Observational Values from H II Region Recombination Lines [1]

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ABSTRACT

We present results of deep echelle spectrophotometry of eight Galactic H II regions located at Galactocentric distances between 6.3 and 10.4 kpc. The data have been taken with the Very Large Telescope (VLT) Ultraviolet Echelle Spectrograph (UVES) in the 3100 to 10360 Å range. We have derived C^{++} and O^{++} abundances from recombination lines for all the objects, as well as O^{+} abundances from this kind of lines for three of the nebulae. The intensity of recombination lines is almost independent of the assumed electron temperature as well as of the possible presence of spatial temperature variations or fluctuations inside the nebulae. These data allow the determination of the gas-phase C and O abundance gradients of the Galactic disk, of paramount importance for chemical evolution models. This is the first time the C gradient is derived from such a large number of H II regions distributed in such a wide range of Galactocentric distances. Abundance gradients are found of the form $\Delta\log(O/H) = -0.044\pm0.010$ dex kpc^{-1}, $\Delta\log(C/H) = -0.103\pm0.018$ dex kpc^{-1}, and $\Delta\log(C/O) = -0.058\pm0.018$ dex kpc^{-1}.

Subject headings: ISM: abundances—H II regions—Galaxy: abundances

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1. Introduction

The analysis of intensity ratios of collisionally excited lines (hereinafter CELs) is the standard method for deriving ionic abundances in ionized nebulae. Almost all the available determinations of the gas-phase Galactic abundance gradients from H II regions observations are based on this kind of analysis (Shaver et al. 1983; Afflerbach et al. 1997; Deharveng et al. 2000). The use of CELs has the disadvantage that their intensity strongly depends on the assumed electron temperature and on the presence of temperature variations or fluctuations over the observed volume of the nebula. The most dramatic effect of temperature fluctuations is that ionic abundances are underestimated if these fluctuations are present in the objects but not considered in the abundance calculations (Peimbert 1967). Recombination lines (hereinafter RLs) of heavy element ions are very faint and have been difficult to observe in nebular spectra. Fortunately, the availability of high efficiency echelle spectrographs in large aperture telescopes makes feasible the measurement of RLs for an increasing number of nebular objects. Several autors have obtained O^{++}/H^{+} and C^{++}/H^{+} from the intensity of O II and C II RLs for the brightest H II regions of the Galaxy (Peimbert, Storey & Torres-Peimbert 1993; Esteban et al. 1998, 1999a,b; Tsamis et al. 2003; García-Rojas et al. 2004; Esteban et al. 2004), all of them have found that abundance determinations from RLs are systematicaly larger than those obtained using CELs, independently of the ion considered. These differences, as well as other discrepancies in the nebular properties derived, can be consistently accounted for assuming a t^2 (mean square temperature variation over the observed volume) in the 0.02–0.05 range. Esteban et al. (1999b) were the first authors who estimated the Galactic C and O abundance gradients from RLs in H II regions, but only with three objects and covering a rather small range of galactocetric distances (from 6.4 to 8.4 kpc, assuming the Sun at 8 kpc). This gradient was later revised by Esteban et al. (2002) and García-Rojas et al. (2004) (hereinafter G04), these last authors included abundances for an additional H II region at 7.46 kpc (NGC 3576). In this paper, we present new values of the C and O gradients obtained from very deep echelle spectra of eight Galactic H II regions located at Galactocentric distances ranging from 6.3 to 10.4 kpc (assuming the Sun at 8 kpc). Some of our sample nebulae were previously observed by our group with other instrumentation: Orion nebula (Esteban et al. 1998), M 8 (Esteban et al. 1999a), and M 17 (Esteban et al. 1999b), but they have been re-observed for this project. Data of some of the objects included in this paper have been already published: NGC 3576 (G04) and Orion nebula (Esteban et al. 2004; hereinafter E04).

2. Observations, Data Reduction, and Line Intensities

The observations were made on 2002 March 11 and 12 and on 2003 March 29, 30, and 31 with the Ultraviolet Visual Echelle Spectrograph, UVES (D'Odorico et al. 2000), at the Very Large Telescope (VLT) Kueyen Telescope in Cerro Paranal Observatory (Chile). We used the standard settings in the two arms of the spectrograph, covering the region from 3100 to 10360 Å . The instrumental setup and the technical aspects of the observations were the same in all cases and are described in detail in G04 and E04. The results included in this paper correspond to a single slit position in each nebula corresponding to the brightest part of the object. The atmospheric dispersor corrector (ADC) was used during the observations in order to avoid the effects of differential atmospheric refraction along the slit. The total exposure time was very different for each case depending on the surface brightness of the nebulae, ranging from 300 to 600 seconds for the Orion nebula and from 2700 to 9612 seconds for S 311. In all the cases, the total exposure time was achieved adding three or more individual spectra in each spectral zone. The slit width was set to 3.0" and the slit length was set to 10" in the blue arm and to 12" in the red arm in the cases of the Orion nebula and NGC 3576 and 3.0"×10" in both arms for the rest of the objects. The effective spectral resolution at a given wavelength is $\Delta\lambda \sim \lambda/8800$. The spectra were reduced using the IRAF[6] echelle reduction package, following the standard procedure. The standard star EG 274 was observed for flux calibration in the cases of the Orion nebula and NGC 3576 (both observed in 2002). The rest of the objects were observed in 2003 and flux calibrated with the standard stars: HD 49798, EG 274, and CD −32 9927. Line intensities were measured as described in G04 and E04 with the SPLOT routine of the IRAF package. Table 1 presents the extinction-corrected intensity of the emission lines relevant to the results concerning to this paper, except for the Orion nebula and NGC 3576, which complete line lists and abundance data have been published in E04 and G04, respectively. The complete line lists of the rest of the objects will be published elsewhere. The reddening coefficient, $C(H\beta)$, was determined by fitting iteratively the observed and theoretical Balmer decrement following the predictions by Storey & Hummer (1995) and is included in Table 2. We have used the reddening law of Seaton (1979) for all the objects listed in Table 1 except in the cases of M8 and M 16 for which we have used the reddening law of Cardelli, Clayton & Mathis (1989) following the prescriptions of Sánchez & Peimbert (1991) and Chini & Wargau (1990). The errors associated with the line intensities have been estimated following G04.

[6]IRAF is distributed by NOAO, which is operated by AURA, under cooperative agreement with NSF.

3. Results and Discussion

In Table 2, we present the adopted electron density, N_e, and temperature, T_e, for each object. The adopted N_e corresponds to the mean of the values obtained from [O II], [S II], [Cl III], and [Fe III] –and [Ar IV] in several of the objects–, weighted by their corresponding uncertainties. In the case of T_e we have adopted two values, one corresponding to the high ionization potential ions, T_{high}, which is calculated as the weighted mean of the temperature obtained from [O III], [S III], and [Ar III] (only temperatures from [O III] were available for M 16 and M 20), and other to the low ionization potential ones, T_{low}, which corresponds to the weighted mean of the values obtained for [O II] and [N II]. In any case, intensity ratios of RLs are almost independent of N_e and T_e and they are almost unaffected by the values assumed for these parameters. The temperature and density determinations were carried out with the IRAF task TEMDEN of the package NEBULAR. More details on the determination of the physical conditions can be found in G04 and E04. The adopted values for N_e, T_{high}, and T_{low} are included in Table 2.

We have adopted T_{high} for the derivation of C^{++}/H^+ and O^{++}/H^+ ratios and T_{low} for O^+/H^+. We have used the effective recombination coefficients of Storey & Hummer (1995) for H I, of Davey, Storey & Kisielius (2000) for C II, and of Storey (1994) for O II. The average of the abundances obtained with the effective recombination coefficients of Péquignot, Petitjean & Boisson (1991) and Escalante & Victor (1992) has been used to obtain the O^+/H^+ ratio. We have used the intensity of the brightest C II line (C II 4267 Å, see Figure 1) to derive the C^{++}/H^+ ratio. Other much fainter lines of $d-f$ and $f-g$ transitions of C II have been observed in all the nebulae except NGC 3603 and S 311. These lines give abundances in agreement with those obtained with C II 4267 Å. The only RLs of O I observed in our spectra are those of multiplet 1. However, there are several bright sky lines in that spectral region and only O I 7771.94 Å can be measured. Unfortunately, a satisfactory deblending of the O I line from sky lines was not possible in some of the objects due to the radial velocity of the nebulae: Orion nebula, M 16, M 17, and S 311. For these four nebulae as well as for NGC 3603 (for which O I lines were not detected) we have determined the O^+/H^+ ratio from the intensity of [O II] lines using NEBULAR and assuming an appropriate value of t^2. The t^2 adopted for each object is also included in Table 2. This parameter has been determined from the weighted mean of the different t^2 values obtained from the comparison of ionic abundances obtained from CELs and RLs of the same ions, the comparison of T_e obtained from CELs and from the Balmer and Paschen discontinuities, as well as a maximum likelihood method applied to the intensity of the brightest He I lines. Details on the derivation of t^2 can be found in G04 and E04. In the case of the O^{++} abundances, the values quoted in Table 2 are the weighted means of the O^{++}/H^+ ratios obtained from the sum of the intensities of the individual lines of the less case-dependent multiplets observed in each nebula following

the prescriptions given in G04 and E04. We have used multiplets number 1, 2, 10 and the $4f-3d$ transitions in the cases of the Orion nebula (E04) and NGC 3576 (G04), multiplets 1, 2, and 10 in the case of M 8 and M 17, and multiplet 1 in M 16, M 20, NGC 3603, and S 311. The lines of multiplet 1 are much brighter than those of the other multiplets and dominate the final mean value, therefore, we have only included the line intensities of multiplet 1 in Table 1, the rest of the O II line intensities of M 8 and M 17 will be published elsewhere.

Once we have the ionic abundances, we can derive the total abundances of the elements. The total O abundance is the sum of the O^+/H^+ and O^{++}/H^+ ratios. In the case of C we have only information about the C^{++}/H^+ ratio. To obtain the final C/H ratio we have used the ionization correction factor (ICF) for the presence of C^+ derived by Garnett et al. (1999) from photoionization models (see their Figure 2). This ICF indicates that the C^+/C^{++} ratio goes from 0.08±0.04 in the case of NGC 3603 to 2.2±0.8 in the case of M20, the two nebulae with the extreme values of excitation.

Figure 2 shows the C/H, O/H, and C/O ratios derived for the eight nebulae of the sample. The Galactocentric distances of the objects have been taken from the stellar photometric distances quoted in the survey of Galactic star-forming complexes of Russeil (2003) and the work on distances to open clusters of Dias et al. (2002). The Sun is assumed to be at a Galactocentric distance of 8 kpc. Simple least-squares linear fits to the data given in Figure 2 give the following gradients:

$$12 + \log(\mathrm{O/H}) = (9.043\pm0.082)-(0.044\pm0.010)R_G \ (\mathrm{r} = 0.647),$$

$$12 + \log(\mathrm{C/H}) = (9.396\pm0.139)-(0.103\pm0.018)R_G \ (\mathrm{r} = 0.905),$$

$$\log(\mathrm{C/O}) = (0.360\pm0.141)-(0.058\pm0.018)R_G \ (\mathrm{r} = 0.762).$$

These gradients and the data used for their derivation correspond to the composition of the ionized gas-phase of the interstellar medium (ISM). Esteban et al. (1998) estimated that C and O abundances of the Orion nebula should be increased about 0.1 dex and 0.08 dex, respectively, to obtain the current gas+dust composition of the local ISM. We do not know if these depletion factors for the Orion nebula can be applied to all the sample objects or if they depend on the particular ionization conditions of the nebulae. In any case, the relatively small dispersion of the C and O abundances for a given distance suggests that the possible differences in the depletion factors should not be large. Therefore, in the absence of further information, we recommend to apply the depletion factors estimated by Esteban et al. (1998) to all the objects prior to compare our abundances with the predicted ones of chemical evolution models. The value of the O gradient we derive is shallower than those obtained by Shaver et al. (1983) (-0.080 dex kpc^{-1}) and Afflerbach et al. (1997) (-0.070 dex kpc^{-1}) but similar to the value of -0.040 dex kpc^{-1} obtained by Deharveng et al. (2000)

and that estimated by Pilyugin (2003) (-0.051 dex kpc^{-1}). All these determinations of the literature are based on the intensity of CELs, therefore, their results depend very much on the exact value of the T_e assumed for each object. In our case, the O gradient we obtain from CELs and assuming t^2=0 is found of the form $\Delta\log(\mathrm{O/H}) = -0.040\pm0.006$ dex kpc^{-1}, which is very similar to the gradient we derive from RLs. The Ne, Ar, and S gradients –which are expected to follow the behavior of O– determined by Martín-Hernández, van der Hulst, & Tielens (2003, and references therein) from ISO data are also consistent with shallower values of the slope. Our C gradient is clearly much steeper than the one we obtain for O. The slope of the C gradient is also steeper than the one obtained by Rolleston et al. (2000) for B stars (-0.070 dex kpc^{-1}). The C/O gradient is an important constraint for chemical evolution models and the radial star formation history of the Galactic disk because the nucleosynthetic origin of both elements is expected to be quite different. We find that the C/O ratio increases with metallicity. Our C/O gradient is similar to that obtained by Garnett et al. (1999) for two nearby spiral galaxies: M 101 and NGC 2403 (-0.04 and -0.05 dex kpc^{-1}, respectively), from the analysis of CELs in the UV domain, and is also similar to that obtained by Smartt et al. (2001) for Galactic B stars (-0.050 dex kpc^{-1}). Models of Galactic chemical evolution to explain the observed gradients will be presented by Carigi et al. (2004, Paper II). C and O are the most important "biogenic elements" and their gradients are paramount: in the study of the Galactic habitable zone (e.g. Lineweaver, Fenner & Gibson 2004 and references therein) as well as to determine the CO to H_2 conversion factor (e.g. Strong et al. 2004 and references therein).

We are grateful to the referee, Dr. Dick Henry, for his careful review of the paper. CE and JG would like to thank the members of the Instituto de Astronomía, UNAM, for their always warm hospitality. This work has been partially funded by the Spanish Ministerio de Ciencia y Tecnología (MCyT) under projects AYA2001-0436 and AYA2004-07466. MP received partial support from DGAPA UNAM (grant IN114601). MTR received partial support from FONDAP(15010003), a Guggenheim Fellowship and Fondecyt(1010404). MR acknowledges support from Mexican CONACYT project J37680-E. LC's work is supported by CONACyT grant 36904-E.

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Table 1. Reddening corrected relevant line ratios (F(Hβ) = 100).

λ_0 (Å)	Ion	M 16	M 8	M 17	M 20	NGC 3603	S 311
3726.03	[O II]	155±6	151±5	46±2	147±6	40±2	165±7
3728.82	[O II]	122±5	106±4	46±2	173±7	25±1	194±8
4267.15	C II	0.27±0.03	0.22±0.01	0.58±0.04	0.17±0.02	0.33±0.06	0.108±0.013
4363.21	[O III]	0.19±0.02	0.29±0.01	0.95±0.05	0.15±0.02	2.5±0.1	0.56±0.02
4638.86	O II	0.040±0.012	0.034±0.005	0.093±0.018	...	0.057:	0.028±0.008
4641.81	O II	0.034±0.012	0.043±0.005	0.128±0.020	0.030:	0.131±0.033	0.028±0.008
4649.13	O II	0.056±0.014	0.041±0.005	0.123±0.019	0.036:	0.172±0.034	0.025±0.008
4650.84	O II	0.050±0.014	0.032±0.005	0.100±0.018	0.017:	0.086±0.029	0.025±0.008
4661.63	O II	0.038±0.013	0.036±0.005	0.119±0.019	0.018:	0.111±0.031	0.024±0.008
4673.73	O II	...	...	0.022:	...	...	...
4676.24	O II	...	0.017±0.004	0.044±0.014	...	0.040:	...
4861.33	H I	100±3	100±3	100±3	100±3	100±3	100±3
4958.91	[O III]	27.8±0.9	33±1	114±3	19.0±0.6	180±5	43±1
5006.84	[O III]	82±3	96±3	335±10	59±2	533±16	126±4
7771.94	O I	0.013:[a]	0.029±0.003	0.025±0.005[a]	0.036±0.006	...	...

[a]Blend with sky emission

Table 2. Some Parameters, Physical Conditions and Chemical Abundances

Parameter	M 16	M 8	M 17	M 20	NGC 3576	Orion neb.	NGC 3603	S 311
R_G (kpc)	6.34[a]	6.41[b]	6.75[a]	7.19[a]	7.46[b]	8.40[a]	8.65[a]	10.43[b]
C(Hβ)	1.21±0.06	0.94±0.03	1.17±0.05	0.36±0.04	1.40±0.07	0.76±0.08	2.36±0.06	0.64±0.04
N_e (cm^{-3})	1120±220	1600±200	470±120	270±60	2800±400	8900±200	5150±750	310±80
T_{high} (K)	7650±250	8040±130	8050±150	7800±300	8500±150	8320±40	9050±200	9050±200
T_{low} (K)	8350±200	8450±150	8870±300	8400±200	8500±150	10000±400	11400±700	9500±250
t^2	0.036±0.006	0.037±0.004	0.033±0.005	0.036±0.013	0.038±0.009	0.022±0.002	0.040±0.008	0.038±0.007
$C^{++}/H^+ \times 10^5$	25±2	20±1	48±4	15±2	28±4	22±1	30±5	10±1
12+log(C/H)	8.76±0.06	8.72±0.03	8.77±0.03	8.69±0.08	8.59±0.07	8.41±0.03	8.51±0.07	8.38±0.07
$O^+/H^+ \times 10^5$	44±10[c]	34±5	10±2[c]	42±7	13±3	14±4[c]	4±1[c]	25±5[c]
$O^{++}/H^+ \times 10^5$	20±2	17±1	48±2	10±5	42±5	37±1	49±6	11±1
12+log(O/H)	8.80±0.06	8.71±0.04	8.76±0.04	8.71±0.07	8.74±0.06	8.65±0.03	8.72±0.05	8.57±0.05

[a]Dias et al. (2002)

[b]Russeil (2003)

[c]Value determined from [OII] lines and assuming the corresponding t^2

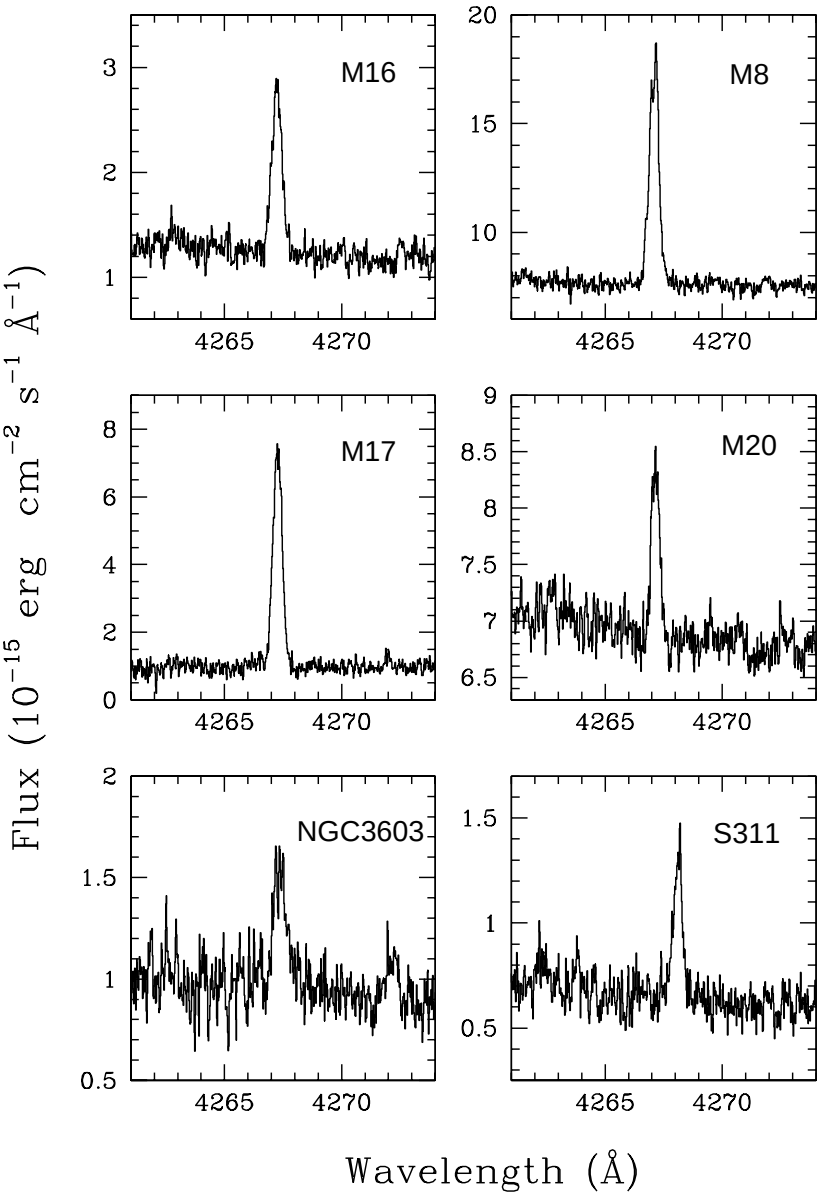


Fig. 1.— Section of the echelle spectra of M 16, M 8, M 17, M 20, NGC 3603, and S 311 showing the C II 4267 Å line, the brightest recombination line of C II in the spectral range observed. Similar plots for the Orion nebula and NGC 3576 have been published in Esteban et al. (2004) and García-Rojas et al. (2004), respectively.

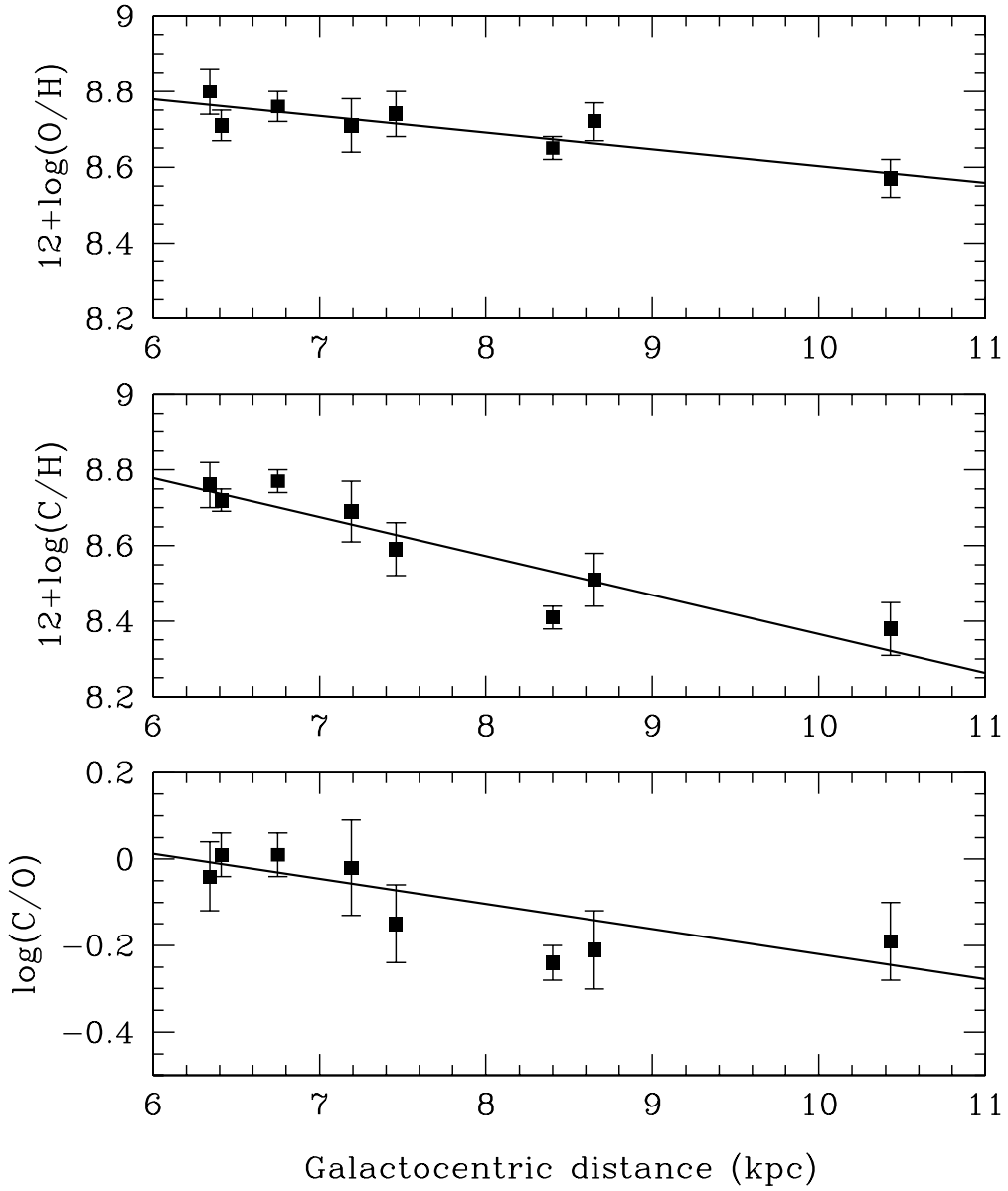


Fig. 2.— Ionized gas phase O, C, and C/O radial abundance gradients of the Galactic disk from H II region abundances determined from recombination lines. The lines indicate the least-squares linear fits to the data. The Sun is located at 8 kpc.