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THE CHEMICAL COMPOSITION OF H II REGIONS IN THE MAGELLANIC CLOUDS: NEW CALCULATIONS USING MODERN ATOMIC DATA

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RESUMEN

Investigamos hasta qué punto los datos atómicos modernos cambian las abundancias encontradas de varias regiones H II en las Nubes de Magallanes. Comparamos nuestros resultados con algunos previamente publicados para seis regiones H II en la SMC y ocho en la LMC. Encontramos que, en general, los nuevos datos atómicos nos llevan a una temperatura electrónica de [O III] $\sim$ 400 K mayor. Usando los nuevos valores diagnosticados, los resultados de abundancia iónica para C^{+2}, N^{+}, O^{+}, O^{+2}, Ne^{+2}, S^{+}, S^{+2} y He^{+} muestran pocas variaciones con respecto a los resultados previos, mientras que el uso de diagnósticos originales con los nuevos datos atómicos dan una abundancia de C^{+2} en la SMC más alta por $\sim$ 0.15 dex y una abundancia de C^{+2} en la LMC que es más baja por $\sim$ 0.09 dex. Las abundancias de los elementos siguen las tendencias generales, decrecen en las regiones de la LMC y aumentan en las de la SMC, pero estas diferencias son $\leq$ 18%. En conjunto, encontramos que las abundancias calculadas en este estudio, usando los datos atómicos modernos, no difieren en forma significativa de las "abundancias recomendadas" para la SMC y la LMC publicadas en Dufour (1984).

ABSTRACT

We investigate the extent to which modern atomic data changes the abundances found from several H II regions in the Magellanic Clouds. We compare our results with those previously published for six SMC and eight LMC H II regions. We find that, in general, the new atomic data lead to an [O III] electron temperature $\sim$ 400 K higher. Ionic abundance results for C^{+2}, N^{+}, O^{+}, O^{+2}, Ne^{+2}, S^{+}, S^{+2}, and He^{+} using the new diagnostic values show little variation from previous results, while use of the original diagnostics with the new atomic data give an SMC C^{+2} abundance that is higher by $\sim$ 0.15 dex and an LMC C^{+2} abundance that is lower by $\sim$ 0.09 dex. Elemental abundances do follow general trends, decreasing for the LMC and increasing for the SMC, but these differences are $\leq$ 18%. Overall, we find the abundances calculated in this study using modern atomic data do not differ significantly from the SMC and LMC "recommended abundances" published in Dufour (1984).

Key words: **ISM: DUST, EXTINCTION — LINE: PROFILES — STARS: MASS LOSS — STARS: PRE-MAIN-SEQUENCE**

1. INTRODUCTION

Studies of the physical properties and chemical abundances of H II regions in the mid 1970s led to the discovery of significant abundance differences between the LMC, the SMC, and the Galaxy. Dufour (1984) summarized the major abundance studies of H II regions in the Magellanic Clouds at that time, and provided recommended abundances for He, C, N, O, Ne, S, Cl, and Ar for the LMC and SMC. These abundances show pronounced deficiencies in the gaseous-phase total elemental abundances of N, O, and Ne compared to the sun and nearby galactic H II regions, with those in the SMC showing the larger deficiencies in all elements studied. The atomic data available for electron impact excitation and transition probabilities used in these studies was to a large extent compiled in Mendoza (1983).

During the last 10 years international teams of atomic physicists and astrophysicists have produced large amounts of atomic data. Two groups in particular have provided atomic data of interest to nebular astrophysics. The Opacity Project concentrated on obtaining accurate photoionization cross sections and oscillator strengths using the R-matrix method. The studies contained data for various ionization stages of almost all astrophysically abundant elements. The Iron Project included relativistic effects in the R-matrix method calculations, and

TABLE 1

SELECTED ABUNDANCE STUDIES OF H II REGIONS IN THE MAGELLANIC CLOUDS

Reference	Instrument	WL range	#LMC	#SMC	Elements
Dufour 1975	scanner + image-tube	λλ3727-7136	4	0	He, N, O, Ne, S
Dufour & Harlow 1977	scanner	λλ3727-6731	0	3	He, N, O, Ne, S
Dufour, Shields, & Talbot 1982	*IUE* vidicon + scanner	λλ1200-7330	4	3	He, C, N, O, Ne, S

strove to compute ion electron impact excitation cross sections. Pradhan & Peng (1994) have compiled a list of recommended data for electron impact excitation and transition probabilities for forbidden transitions among low-lying levels of atomic ions prevailent in nebular astrophysics using the results from these and other studies. Their tabulation updates and extends the compilation of Mendoza (1983).

We discuss here new physical properties and abundances for select H II regions in the Magellanic Clouds from several studies cited in Dufour (1984). We adopt some of the new atomic data presented in Pradhan & Peng (1994) into our five-level atom approximation code, and compute electron temperatures and densities, and ionic and elemental abundances. We compare these results with those from the original studies and with the recommended abundances given in Dufour (1984). We derive new average elemental abundances for the LMC and SMC, and investigate the extent to which modern atomic data changes the abundances found for H II regions in the Magellanic Clouds.

2. PHYSICAL CONDITIONS

The studies selected for this work are shown in Table 1, along with the instruments, wavelength range, number of H II regions from the LMC and SMC, and the elements investigated. Space considerations prevent a tabulation of the line intensities here. We note that the intensities used were those from the original papers except for SMC N66A λ4471, most of the λ4959 fluxes from Dufour, Shields, & Talbot (1982), and for all of the He I lines. SMC N66A $I_{\lambda 4471}$ was determined using the relation $I_{\lambda 5876} = 2.665 I_{\lambda 4471}$ from Osterbrock (1989) p. 87, with $T_e = 15\,000$ K and $N_e = 100$ cm^{-3}. For the Dufour et al. (1982) $I_{\lambda 4959}$ intensities, $I_{\lambda 5007} = 3.0 I_{\lambda 4959}$ was used in place of the missing values. This latter relation was determined from observations of gaseous nebulae by Peimbert & Costero (1969), Peimbert & Torres-Peimbert (1971), Simpson (1973), and by the theoretical ratio of the transition A-values referenced in Mendoza (1983). The He I lines were corrected for collisional excitation effects for this study, using the collision-to-recombination correction factors derived by Kingdon & Ferland (1995) and our new T_e and N_e diagnostics. In all cases these corrections were $\leq 4\%$.

The electron temperatures were calculated using the [O III] diagnostic ratio λλ4959+5007/λ4363. For comparison purposes, we assumed $t^2 \sim 0$ in all cases. The results are presented in Table 2. In general, the derived electron temperatures are higher by ~ 400 K. The Dufour (1975) results are lower by ~ 200 K. However, in that study the [O III] temperatures were derived from tables of $I_{\lambda 4959} + I_{\lambda 5007}/I_{\lambda 4363}$ published by Eissner et al. (1969) using only photoelectrically measured $I_{\lambda 5007}/I_{\lambda 4363}$ ratios. The results are within the probable errors given. We note that the atomic data used for [O III] is from Mendoza (1983). However, this data was first published in the early eighties, and thus pre-dates most of the original data sets presented. (We reject the values recommended by Pradhan & Peng (1994) for [O III] because a ratio of their A-values give the relation $I_{\lambda 5007} = 7.3 I_{\lambda 4959}$, which is in conflict with the observational evidence referenced above.)

Electron densities were derived from the [S II] diagnostic ratio λ6717/λ6730 whenever possible. In Dufour & Harlow (1977) this ratio was not given, and their value $N_e = 100$ cm^{-3} was adopted for the corresponding nebulae. Dufour (1975) ratios were at or near the low density limit in all cases except for LMC N160A. Thus, we adopted their value $N_e = 500$ cm^{-3} for all the nebulae except LMC N160A, where we calculate a density of $N_e = 300$ cm^{-3}. In Dufour et al. (1982) the [S II] ratios for nebulae SMC N66A and SMC N66NW were near the low density limit and we adopt $N_e = 300$ cm^{-3} and $N_e = 100$ cm^{-3}, respectively, from their work. Our calculated densities for the remaining nebulae, SMC N81, LMC N4A, LMC N79A, LMC N157, and LMC N159, were 450, 250, 950, 650, and 150 cm^{-3}, respectively. Unless the densities of the individual H II regions are substantially higher than the values used here, this treatment is not a significant source of error in the results.

TABLE 2

ELECTRON TEMPERATURES

Study	Nebula	Original Study T_e (K)	Present Study T_e (K)
Dufour &	SMC N66SE	11,800±500	12,300±400
Harlow 1977	SMC N83	11,600±650	12,050±400
	SMC N90	12,100±650	12,600±400
Dufour 1975	LMC N11B	9,400±350	9,300±400
	LMC N44B	11,500±750	11,000±600
	LMC N55A	10,000±400	9,800±500
	LMC N160A	9,750±300	9,600±250
Dufour, Shields,	SMC N66A	12,700±500	13,200±940
& Talbot 1982	SMC N66NW	12,000±500	12,600±850
	SMC N81	12,100±500	12,400±900
	LMC N4A	9,000±500	9,300±500
	LMC N79A	9,200±500	9,400±1100
	LMC N157	10,100±650	10,500±1400
	LMC N159	10,300±650	10,700±600

3. ABUNDANCE CALCULATIONS

Space considerations prevent a detailed discussion of the ionic abundances calculated. Elemental abundances from the current and original studies are tabulated in Tables 3 and 4. Note that the abundances are listed using the relation 12+log$N(X)/N(H)$. The method of computation for each element is outlined below:

Helium - The helium abundance was derived from the intensities of the He I λ4471, λ5876, and λ6678 lines using the [O III] temperature, the recombination coefficients of Brocklehurst (1971, 1972), and weighting λ5876 twice as heavily as λ4471 and λ6678. For comparison with the Dufour (1984) study, we assume that corrections for the amount of neutral helium present in the H II regions are small, and adopted He/H = He^+/H^+.

TABLE 3

ELEMENTAL ABUNDANCES: ORIGINAL RESULTS

Study	Nebula	He	C	N	O	Ne
Dufour &	SMC N66SE	10.94	...	6.56	8.07	7.34
Harlow 1977	SMC N83	10.89	...	6.42	8.04	7.24
	SMC N90	10.92	...	6.47	8.03	7.29
Dufour, Shields,	SMC N66A	10.90	7.12	6.45	7.98	7.35
& Talbot 1982	SMC N66NW	10.92	7.17	6.66	8.06	7.33
	SMC N81	10.93	7.18	6.65	8.09	7.35
Dufour 1975	LMC N11B	11.00	...	6.86	8.58	7.79
	LMC N44B	10.94	...	6.72	8.46	7.77
	LMC N55A	11.01	...	6.70	8.44	7.48
	LMC N160A	11.05	...	6.99	8.59	7.90
Dufour, Shields,	LMC N4A	10.91	7.98	6.93	8.45	7.77
& Talbot 1982	LMC N79A	10.90	8.06	7.06	8.49	7.67
	LMC N157	10.95	7.69	6.92	8.27	7.61
	LMC N159	10.93	7.79	6.84	8.27	7.64

TABLE 4

ELEMENTAL ABUNDANCES: CURRENT RESULTS

Study	Nebula	He	C	N	O	Ne
Dufour & Harlow 1977	SMC N66SE	10.95	···	6.64	8.04	7.22
	SMC N83	10.90	···	6.47	8.01	7.12
	SMC N90	10.91	···	6.52	8.00	7.18
Dufour, Shields, & Talbot 1982	SMC N66A	10.91	7.16	6.49	7.96	7.24
	SMC N66NW	10.92	7.18	6.65	8.01	7.20
	SMC N81	10.92	7.26	6.59	8.08	7.28
Dufour 1975	LMC N11B	10.96	···	6.82	8.41	7.52
	LMC N44B	10.84	···	6.77	8.40	7.73
	LMC N55A	10.84	···	6.67	8.31	7.24
	LMC N160A	10.96	···	6.99	8.43	7.64
Dufour, Shields, & Talbot 1982	LMC N4A	10.91	7.94	7.04	8.43	7.65
	LMC N79A	10.88	8.05	7.12	8.48	7.61
	LMC N157	10.93	7.47	6.99	8.26	7.61
	LMC N159	10.93	7.76	6.93	8.22	7.52

Carbon - The carbon abundances for the SMC and LMC are entirely from the study by Dufour et al. (1982). Consequently, the ionization correction from their model calculations, $0.92\times C/H = C^{++}/H^{+}$, was adopted for comparison purposes. We note that, although the new elemental carbon abundances show little change from their original values, employing the T_e's and N_e's from the original studies with the new atomic data results in abundances $\sim$ 0.15 dex higher for the SMC and $\sim$ 0.09 dex lower for the LMC.

Nitrogen - Although N^{+} is usually a minor fraction of the total nitrogen abundance in the high ionization Magellanic H II regions, the models in Dufour et al. (1982) suggest the standard ionization correction scheme $N/O = N^{+}/O^{+}$ applies reasonably well for the H II regions under consideration. Thus, Dufour (1984) used this relation to calculate the nitrogen abundance for the nebulae in the original study, and for comparison purposes we do as well.

Oxygen - Essentially all of the oxygen in the Magellanic H II regions is in the form of O^{+} and O^{++}. Thus, we simply summed the ionic abundances to get the elemental abundance, $O/H = O^{+}/H^{+} + O^{++}/H^{+}$.

Neon - Calculations for Ne are similar to N in that differences in charge exchange rates between the various ions of Ne and O argue against the standard ICF approach. However, for the purposes of this study, we adopt the traditional ionization correction relation for Ne, $Ne/O = Ne^{++}/O^{++}$, but note this limitation.

Sulphur - Various issues argue against using the simple sulphur ionization correction relation $S/O = S^{+}/O^{+} + S^{++}/O^{+}$. We do not investigate a proper treatment of elemental sulphur abundances here.

4. ABUNDANCE RESULTS

Table 5 presents average abundance results and errors (rms standard deviations) from Dufour (1984) and from the selected study of Magellanic H II regions discussed here. For all elements studied, the average LMC abundances decreased slightly, with carbon and neon showing the greatest change. SMC abundances for helium, carbon, and nitrogen increased slightly, with those for oxygen and neon essentially remaining the same. In all cases the difference between studies is within the given error.

Our treatment and data set for carbon parallels that of Dufour (1984). The average LMC carbon abundance decreased by $< 18\%$; the average SMC carbon abundance increased by $\sim 9\%$. We note however, that this data set is small and a single result for one H II region in each Cloud is largely responsible for these percentages. Thus, we conclude our recommended carbon abundances for the LMC and SMC do not differ significantly from those given in Dufour (1984). We note that for the other elements presented, this work studies a small subset of the Magellanic H II regions considered by Dufour (1984). Thus, although these results indicate little change between the two studies, a more extensive treatment is needed to fully investigate the effects of using modern atomic data to determine abundances from H II regions in the Magellanic Clouds.

TABLE 5

ABUNDANCE RESULTS FOR H II REGIONS IN THE MAGELLANIC CLOUDS

Reference	He	C	N	O	Ne
		Large Magellanic Cloud			
Dufour 1984	10.93±0.02	7.90±0.15	6.97±0.10	8.43±0.08	7.64±0.10
This Study	10.91±0.05	7.81±0.22	6.92±0.14	8.37±0.09	7.55±0.14
		Small Magellanic Cloud			
Dufour 1984	10.90±0.01	7.16±0.04	6.46±0.12	8.02±0.08	7.22±0.12
This Study	10.92±0.02	7.20±0.04	6.56±0.07	8.02±0.04	7.21±0.05

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