THE COMPOSITION OF H II REGIONS IN THE MAGELLANIC CLOUDS

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ABSTRACT

The state of our knowledge concerning the chemical composition of H II regions in the Magellanic Clouds is reviewed. New abundances derived from all modern published spectroscopy are presented. Some of the implications of the results regarding the nucleosynthesis of the elements and galactic chemical evolution are noted.

1. RECENT OBSERVATIONAL STUDIES AND BASIC RESULTS

Studies of the physical properties of H II regions in the Magellanic Clouds began in the late 1950s (Johnson 1959) and has continued at an active pace since. A discussion of the studies made prior to 1974 can be found in the review by Dufour (1976). The "modern age" of abundance studies of H II regions in the Clouds began in the mid 1970s (see Table 1) when four investigations were published by Peimbert and Torres-Peimbert (1974, 1976), Aller et al. (1974), and Dufour (1975). Compared to previous studies, these were notable in (a) the relatively high quality of the spectral data, (b) the direct measurement of electron temperatures and densities in most of the numerous nebulae observed, (c) the use of modern diagnostic techniques and atomic data in the abundance calculations, and (d) the discovery of significant abundance differences between the LMC, SMC, and the Galaxy. Collectively, these studies provided a picture of the physical conditions and chemical composition of the H II regions in the Magellanic Clouds that has changes relatively little since.

The four studies showed conclusively that the H II regions in the LMC and SMC had 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. Compared to the sun, O and Ne were found to be deficient (relative to H) by factors of about 2.5 (-0.4 dex) in the LMC and 6 (-0.8 dex) in the SMC. Of all of the elements studied, N showed the largest deficiency: factors of about 6 (-0.8 dex) in the LMC and 25 (-1.4 dex) in

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the SMC. Relative to the Orion Nebula, these deficiencies were smaller but no less significant. In addition, Aller et al. noted that the deficiencies of S, Ar, and Cl (again relative to H) in the LMC are roughly similar to those of O and Ne — a result further substantiated by Dufour for both clouds using deeper photographic spectra. None of the investigations found significant evidence of radial (or other) composition gradients in the Clouds. Peimbert and Torres-Peimbert, using a more detailed analysis and smaller corrections for neutral He, found N(He)/N(H) = 0.084 ± 0.005 for the LMC and N(He)/N(H) = 0.078 ± 0.005 for the SMC.

These interesting findings concerning the composition of the H II regions stimulated additional spectroscopic (and other) studies of emission nebulae in the Clouds that included planetary nebulae and supernova remnants as well (cf. the reviews by Peimbert and Dopita in this volume). The studies of PN by Webster (1976), Osmer (1976), and Dufour and Killen (1977) included several small semi-stellar H II regions, as well as PN, and the results on these generally confirmed the findings of the previous investigations of the larger H II regions. Dufour and Harlow reported photoelectrically measured line strengths for 13 emission lines in 10 SMC H II regions, most notably the λλ4471, 5876, and 6678 He I lines that are crucial for determining accurate He abundances. Pagel et al. reported new observations of 6 LMC and 17 SMC H II regions made with the IDS and IPCS spectrometers at the AAT covering the λλ3575-8500 wavelength region, and used the new and previously published data to analyze the composition of a total of 19 LMC and 23 SMC H II regions. These new studies resulted in improved abundances for N, O, and Ne in the LMC and SMC, but not significantly different from those previously published. Dufour and Harlow's study is most notable in that it derived probably the most representative value for the He abundance of the SMC at the time: N(He)/N(H) = 0.081 ± 0.005 (based on 10 nebulae), which was slightly larger than that found by

Table 1. Major Abundance Studies of H II Regions in the Magellanic Clouds

Reference	Instrument	WLrange	#LMC	#SMC	Elements
Peimbert & Torres-Peimbert 1974	scanner	3727-7330	4	0	He, N, O, Ne
Aller et al. 1974	scanner + image-tube	3727-7330	20	10	He, N, O, Ne, S, Ar
Dufour 1975	scanner + image-tube	3727-7136	11	3	He, N, O, Ne, S, Cl, Ar
Peimbert & Torres-Peimbert 1976	scanner	3727-7330	0	3	He, N, O, Ne
Dufour & Harlow 1977	scanner	3727-6731	0	10	He, N, O, Ne, S, Ar
Pagel et al. 1978	IDS + IPCS	3575-8500	19	23	He, N, O, Ne, S, Cl, Ar
Aller et al. 1979	scanner + image-tube	3727-7330	16	6	He, N, O, Ne, S, Cl, Ar
Dufour et al. 1982	IUE vidicon + scanner	1200-7330	4	3	He, C, N, O, Ne, S, Ne, S, Cl, Ar

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Peimbert and Torres-Peimbert (1976): 0.078 ± 0.005 (based on 3 nebulae). Pagel et al.'s study did not impact the He abundance problem, but did contribute significantly to the accuracy of the determination of representative abundances of the other elements, particularly S, Cl, and Ar. More recently, Dennefeld and Stasinska (1983) published a reanalysis of the S abundances in several LMC, SMC, and MWG H II regions, based on new observations of the IR lines of [S III], which they derived S/H ratios for the LMC and SMC nebulae lower by a factor of about 2 compared to most previous studies.

In essentially all of the previously cited studies, the investigators adopted the ionization correction factor (ICF) approach first applied to galactic H II regions by Peimbert and Costero (1969). In this approach, the ionization corrections for various observable ions are largely estimated from the O^+/O^{+2} ratio based on comparison of ionization potentials of O^+, O^{+2}, and the ion. A potentially more accurate method of deriving total elemental abundances in H II regions is through the use of sophisticated nebular models based on matching the observed spectrum and physical conditions of a nebula. Such procedures have recently been applied to H II regins in the Magellanic Clouds by Aller et al. (1979) and by Dufour et al. (1981, 1982). Not only do these procedures result in more accurate determination of ionization corrections to use in deriving elemental abundances from the observable ions, but they also give an estimate of the extent of the temperature fluctuations in a nebula and the temperatures appropriate to zones for each ion.

In addition to the application of model analysis techniques, the study of Dufour et al. (1982) presented new observational data on the ultraviolet spectra of 4 LMC and 3 SMC H Ii regions using the IUE satellite. This permitted the first determination of the gaseous-phase C abundances in the H II regions of the Magellanic Clouds. In a prior preliminary paper, Dufour et al. (1981) found the C/H ratio in 3 SMC H II regions to be a factor of 8 (-0.9 dex) lower than in the sun. Later, based on additional IUE data, Dufour et al. (1982, cf. also Dufour and Shields 1982) found C/H lower in the LMC and SMC by factors of 6 (-0.75 dex) and 30 (-1.49 dex), respectively, compared to the sun. Recent radio studies of CO in the Clouds (cf. the review by Israel in this volume) and the weakness of the λ2200 graphite feature in the UV extinction curves for the LMC and SMC (cf. the review by Nandy in this volume) further substantiate the existence of a C deficiency in the ISM of the Clouds.

2. SUMMARY OF RESULTS AND "RECOMMENDED ABUNDANCES" FOR THE LMC AND SMC

In Table 2 the averaged abundance results of the major recent studies of H II regions in the LMC and SMC are presented (note that those of the Peimberts have been rederived using smaller temperature fluctuations and more modern atomic data as noted in Lequeux et al. 1979). At the bottom of the table are newly calculated "recommended abundances" for the LMC and SMC derived by the author using the model-based analysis techniques of Dufour et al. (1982) applied to all of the spectral data from the various

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Table 2. Abundance Results for H II Regions in the Magellanic Clouds

Reference	He	12 + log N(X)/N(H) (except He)						
		C	N	O	Ne	S	Cl	Ar
Large Magellanic Cloud								
PTP 1974(t^2 = 0.035)*	0.084		7.21	8.50	7.64			
(t^2 = 0.000)	0.084		7.03	8.34	7.44			
Aller et al. 1974	0.098		6.94	8.46	7.83	7.2		
Dufour 1975	0.102		6.80	8.43	7.64	7.15	5.01	7.10
Pagel et al. 1978			6.88	8.39	7.61	6.8	4.9	6.35
Aller et al. 1979			7.02	8.43	7.77	6.90		6.35
Dufour et al. 1982	0.083	7.90	6.94	8.38	7.68	7.01		6.10
Small Magellanic Cloud								
Aller et al. 1974	0.100		6.28	7.97	7.40	6.5		6.0
Dufour 1975	0.093		6.49	8.05	7.18	7.15		7.02
PTP 1976 (t^2 = 0.035)*	0.078		6.49	7.99	7.13			
(t^2 = 0.000)	0.078		6.41	7.89	7.03			
Dufour and Harlow 1977	0.081		6.48	8.02	7.29	6.4		
Pagel et al. 1978			6.41	7.98	7.16	6.4	4.5	5.94
Aller et al. 1979			6.45	8.10	7.58	6.29		5.86
Dufour et al. 1982	0.083	7.16	6.60	8.05	7.34	6.61		5.77
LMC Recommended	0.085	7.90	6.97	8.43	7.64	6.85	4.84	6.20
(rms error)	±0.004	±0.15	±0.10	±0.08	±0.10	±0.11	±0.20	±0.06
SMC Recommended	0.080	7.16	6.46	8.02	7.22	6.49	4.7:	5.78
	±0.003	±0.04	±0.12	±0.08	±0.12	±0.14		±0.12

*Note: The PTP 1974 and 1976 abundances shown are those rederived in Lequeux et al. (1979).

studies (and including the model results of Aller et al. 1979).

A number of comments regarding the new and old results and some of the associated problems involved in the calculations for the different elements are in order: Helium — Evaluation of the He/H abundance in the H II regions of the Clouds essentially reduces to a problem of determining and using only the best quality data on the He I lines and estimating the magnitude of the corrections for neutral He. The results are relatively insensitive to temperatures adopted. Values of He^+/H^+ in 14 LMC and 15 SMC H II regions were calculated using published spectrophotometry that contained measurements of at least two of the ratios: I(4471)/I(Hγ), I(5876)/I(Hα), and I(6678)/ I(Hα) — and the results retained only if at least two He^+/H^+ values for the groups of LMC and SMC H II regions showed little indication of depending on ionization level (most had $O^{+2}/O^+ >$ 0.5). This observation, coupled with recent models, suggest that the correction for He^0 in these large extended nebulae is negligible in those with ionization fractions $X(O^{+2}) > 0.6$. Consequently, the He^+/H^+ values 8 LMC and 10 SMC nebulae meeting these requirements were averaged to get the final He/H results for the LMC and SMC shown in Table 2. The errors (rms standard deviations) in the averages are smaller than in the previous studies of the Peimberts and of Dufour and Harlow. Carbon — The recommended C abundances for the LMC and SMC were taken straight from the study by Dufour et al. (1982) based on IUE observations of the λ1909 [C III] lines in 4 LMC and 3 SMC H II regions and ionization corrections made by model calculations. Newer IUE data recently obtained from additional nebulae confirm these results. Nitrogen — Since N^+ is usually a very minor fraction of the total N abundance in the high ionization H II regions of the Clouds, and charge exchange with H is probably different for the ions of O and N, it is potentially dangerous to use the usual ICF approach based on the assumption that $N/O = N^+/O^+$. However, the models in Dufour et al. (1982) suggest that $X(N^+) \approx 0.96\ X(O^+)$ in the high excitation low density H II regions of the Clouds, and therefore, I used the standard ICF approach applied to data on 12 LMC and 16 SMC H II regions that had good [O III] temperatures (±10% accuracy) to derive average N/H values for each nebula; which were then combined with the model results of Aller et al. (1979) to get the final galaxy averages based on a total of 20 LMC and 16 SMC H II regions. Oxygen — Since essentially all of the O in the H II regions of the Clouds is in the form of O^+ and O^{+2}, the accuracy of the oxygen abundances in the H II regions primarily depend on the quality of the two ionic abundances — and this to a large extent depends on the quality of the temperature determinations. While the models suggest that slightly different temperatures should be used for O^+ and O^{+2}, the effect is small, so I just averaged all data on O/H abundances for LMC and SMC H II regions that were based on accurate electron temperatures observed by the various investigations (including the data from Aller et al. 1979). Neon — The situation for Ne is similar to N in that charge exchange rate differences between the various ions of Ne and O make the standard ICF approach dangerous. The models in Dufour et al. (1982) suggest that $X(Ne^{+2}) \approx 1.1\ X(O^{+2})$, so I used this ICF to rederive Ne/H in the various H Ii regions and combined the data with the results of Aller et al. (1979). Sulphur, Chlorine, and Argon — The ICF's and the atomic data for the observable ions of these are subjects of much debate at present. Pagel et al. (1978) gives a good discussion of the problems involved with previous ICF approaches, which usually result in the S/O, Cl/O, and Ar/O ratios for individual H II regions in each Cloud varying with ionization level. A more critical study of the ICF problem and model inferences regarding S have been made by Dennefeld and Stasinska (1983), in which they utilized new observations of the strong IR [S III] lines in several LMC and SMC H II regions in their analysis. While their results were more consistent with ionization level, the final S/H values for the Clouds were about a factor of 2 lower than previous studies. I calculated S/O, Cl/O, and Ar/O with the available data using the model-inferred ICF's derived in Dufour et al. (1982, based on Model L), and these showed little variation with ionization level. However, the resulting S/H ratios were significantly larger than found by Dennefeld and Stasinska, and probably larger than in reality. Therefore, as a compromise, these S/H values were averaged with the results of Dennefeld and Stasinska for nebulae in common to get the recommended S/H results given in Table II. The results for Cl and Ar in Table 2 are based solely on the Dufour et al. model-inferred ICFs.

3. DISCUSSION: SOME IMPLICATIONS OF THE ABUNDANCE DEFICIENCIES

In Table 3 below, the "recommended abundances" derived for the LMC and SMC are compared with those of the sun (Ross and Aller 1976, Lambert 1978) and galactic H II regions in the solar neighborhood (Shaver et al. 1983, Dufour et al. 1982). Some of the implications of the well established abundance deficiencies in the LMC and SMC compared to the solar neighborhood will be noted in the remainder of this paper. A good discussion of these and other implications of the Clouds' results, along with those from stellar and nebular studies of other galaxies, can be found in the excellent review of Pagel and Edmunds (1981).

3.1. Applicability of the Simple Evolutionary Models to the Clouds

Pagel et al. (1978) made a detailed comparison between the abundance results for the LMC and SMC H II and the expectations of simple chemical evolution models. They noted that the apparent lack of significant abundance gradients in the Clouds suggested that they are well mixed systems which (along with many other metal-poor irregulars) follow the expectations of the simple "closed box" model with instantaneous recycling and no infall. Such a model predicts that the mass fraction of heavy elements, Z, in a galaxy is related to the fraction of gas mass to total mass, μ, by the relation: $Z = -p \ln \mu$, where p is the "yield" of the elements. While they found that the individual H II regions did not follow the relation in spatial detail, the average Z (inferred from O, which is presumed to result totally from primary nucleosynthesis processes) for each Cloud varied with μ in a manner analogous to the outer regions of M101 and M33 for the above equation with a yield of $p \approx 0.003$ by mass. This global behavior of the Clouds was further substantiated by Lequeux et al. (1979) using the Clouds' data with those of six other irregulars. They found a yield of 0.004 ± 0.001 which agreed best with those computed by Chiosi et al. (1978) with mass loss and a power law IMF with a slope of 2. Dufour et al. (1982) derived yields for the presumably primary elements C and O individually and they found the results consistent with massive star nucleosynthesis models for an IMF exponent $7/3 < \alpha < 10/3$ if mass loss is negligible, or with $4/3 < \alpha < 7/3$ if mass loss is significant. They also noted that C/H did not follow the expectations of the simple model and

Table 3. Comparative Abundances

Object	[He]	[C]	[N]	[O]	[Ne]	[S]	[Cl]	[Ar]	[C/O]	[N/O]
sun	11.03	8.65	7.96	8.87	8.05	7.23	5.5:	6.57	-0.22	-0.91
MWG H II	11.00	8.46	7.57	8.70	7.90	7.06	5.16	6.42	-0.24	-1.13
[LMC/sun]	-0.10	-0.75	-0.99	-0.44	-0.41	-0.38	-0.7:	-0.37	-0.31	-0.55
[LMC/H II]	-0.07	-0.56	-0.60	-0.27	-0.26	-0.21	-0.32	-0.22	-0.29	-0.33
[SMC/sun]	-0.13	-1.49	-1.50	-0.85	-0.83	-0.74	-0.80	-0.79	-0.64	-0.65
[SMC/H II]	-0.10	-1.30	-1.11	-0.68	-0.68	-0.57	-0.5:	-0.64	-0.62	-0.43

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that deriving Z for metal-poor galaxies based only on the observed O/H value is dangerous since C/O and Fe/O may be much lower than solar values.

3.2. CNO Nucleosynthesis

The result that, until recently, N was observed to show the largest deficiency of all of the elements studied in the H II regions of the Clouds, coupled with similar behavior observed in other galaxies of not following the simple model, prompted speculation that most of the N resulted from secondary nucleosynthesis processes (e.g., Truran 1977), such as processing of C by the CNO cycle in H-burning shells of stars. This N would then be injected into the ISM from intermediate mass stars via planetary nebulae and novae. However, the similarity of the observed N/O ratio in the Clouds and in many other very metal-poor irregulars have led others to propose that a substantial primary component of N exists (cf. Edmunds and Pagel 1978 and references therein). If N is purely a secondary element from C, then the simple model predicts that N/C would be proportional to C/H. The C abundances of Dufour et al. (1982) for the Clouds show that, at least for these metal-poor systems, N/C decreases with increased C/H. They interpret this result as suggesting that most of the N in metal-poor systems is primary and that most of the C enrichment arises from less massive stars than those which produce most of the primary N. However, they point out that in evolved systems, N/C would increase as the secondary production of N from planetary nebulae and novae begin to dominate the chemical enrichment.

3.3. The Pre-Galactic He Abundance and Big Bang Nucleosynthesis

Peimbert and Torres-Peimbert (1974, 1976) showed that the small, but statistically significant He deficiencies in the Clouds coupled with those of the other primary elements suggested a chemical enrichment scenario for galaxies characterized by $\Delta Y/\Delta Z \approx 2.7$. They also derived a pre-galactic He abundance value (by mass) of $Yp = 0.228 \pm 0.014$ and noted that this implied an open universe for $H_o > 16$ km s^{-1} Mpc^{-1} from standard big bang models. Using the Peimbert's He/H results for the Clouds with those of other metal-poor irregulars, Lequeux et al. (1979) derived very similar results. Several subsequent studies of abundances in spiral and irregular galaxies suggest $\Delta Y/\Delta Z \simeq 3$ and $Yp \simeq 0.23$ (Serrano and Peimbert 1981).

4. CONCLUDING REMARKS

While we have come a long way in the study of the composition of the H II regions in the Magellanic Clouds and have apparently accurate information on the abundances of He, C, N, O, Ne, and probably Ar, much can still be done. Deeper optical spectra are needed to improve the determinations of S and Cl, as well as possibly obtaining Fe via the very weak [Fe II] and [Fe III] lines. Observatins in the UV, IR, and radio wavelength regions offer great potential in improving our understanding of physical conditions and determning the abundances of other elements like Mg and Si. The H II regions in the Magellanic Clouds are the most accessible example of the large low density H II regions which dominate the ISM in more distant galaxies, and therefore an understanding of those in the Clouds is necessary before the true potential of extragalactic H II region studies can be fully exploited.

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DISCUSSION

Graham: Do you think the reported abundance gradients in the LMC are marginal at best?
Dufour: The Pagel et al. (1978) result: $d(\log O/H) / dR = 0.03 \pm 0.02$ is definitely marginal. With these data I find a less obvious gradient in N/H and O/H, and none in N/O.
Graham: Would you or Peimbert comment on Bob Williams recent suggestion that there may be substantial nitrogen enrichment in the Magellanic Clouds from novae?
Dufour: Yes, probably Manuel Peimbert should comment; he has restudied Williams results and believes that novae are less important than planetary nebulae.
Peimbert: I think that is a very provocative idea. I find three problem areas that should be clarified before the importance of nitrogen enrichment by novae is established: a) the N produced by novae, according to stellar evolution models, is the isotope N^{15} while in the solar neighborhood N^{14}/N^{15} is larger than 100; b) the shell masses of novae might have been overestimated if the filling factor is very small, that is in the presence of spatial density fluctuations; and c) I think that we should try to obtain masses and chemical compositions of the novae in the LMC.
Dopita: It is interesting that the SNR's (see IAU Symp. 101) in Magellanic irregulars also give constant N/O ratios from galaxy to galaxy. The study of SNR's has the potential to give very accurate C, Si, Ca and Fe abundances from their extremely rich UV spectra, and should furnish a very good check on chemical evolution theories.
Dufour: I agree totally. In fact, Don Cox, John Raymond, and I are working on modelling the SNR's in IC1613 and NGC6822 using my SMC and LMC abundances with the aim of matching their spectra for abundance determinations. I believe that SNR's have great potential in this area, particularly for elements like Fe and Ca, and commend you on your pioneering efforts in the past few years.
Lequeux: I would like to caution about any derivation of the yield from the Z vs. M(gas)/M(tot) relation in irregular galaxies. At the time I published my paper with the Peimberts and Talent wrote his thesis, there seemed to be a nice Z vs. M(gas)/M(tot) relation, but more recent work demonstrated the existence of exceptions. The most striking cases are the blue compact galaxies IZw18 and IZw36, studied by Viallefond, Thuan and myself. These objects are very metal deficient but have a small M(gas)/M(tot) (of the order of 0.1 - 0.2). This points to complications like accretion of external gas, changes in the IMF or galactic winds, which may well occur also on most irregular galaxies.
Dufour: I believe that your point is most correct and important. We, for example, find He/H in IC1613 exceptionally large for its Z inferred from O/H. Since these small systems are sensitive to external and internal effects (e.g., infall, encounters, etc.), I am sure that a good percentage of them will have "abnormal" characteristics. However, I think the group of nearby irregulars studied by Talent in his thesis is an exceptionally good set for such comparisons since they are sufficiently resolved to obtain total masses by rotation curves, gas masses by HI fluxes, and accurate astration (μ) values. This is not true for most of the Zwicky and the compact systems because of their greater distances.

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