Model nebulae and determination of the chemical composition of the Magellanic Clouds

(gaseous nebulae/galaxies)

L. H. ALLER*, C. D. KEYES*, AND S. J. CZYZAK†

*Department of Astronomy, University of California, Los Angeles, California 90024; and †Department of Astronomy, Ohio State University, Columbus, Ohio 43210

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ABSTRACT An analysis of previously presented photoelectric spectrophotometry of HII regions (emission-line diffuse nebulae) in the two Magellanic Clouds is carried out with the aid of theoretical nebular models, which are used primarily as interpolation devices. Some advantages and limitations of such theoretical models are discussed. A comparison of the finally obtained chemical compositions with those found by other observers shows generally a good agreement, suggesting that it is possible to obtain reliable chemical compositions from low excitation gaseous nebulae in our own galaxy as well as in distant stellar systems.

Diffuse gaseous nebulae, often called HII regions, are of considerable value in studies of the chemical compositions of spiral and irregular galaxies. Besides hydrogen and helium, which are represented by their recombination lines, we observe the so-called forbidden lines of nitrogen, oxygen, neon, sulfur, argon, and occasionally chlorine, in various stages of ionization. Hydrogen and most of the helium are primordial; the atoms of all other elements have been built in previously existing stars. Only very massive stars, some of which may end their lives as supernovae, develop cores that are sufficiently hot and dense to build up nuclei of heavier elements such as sulfur and argon. Stars within the range from one to five solar masses are believed to be primarily responsible for the enhancement of helium, carbon, and neon. From a comparison of the N/H, O/H, Ne/H, Ar/H, etc., abundance ratios from one point in a galaxy to another, or between galaxies, we can assess the effectiveness of various element-building processes and even infer something about the masses of the stars taking part in these events at different epochs in the history of any given stellar system.

Much attention has been paid to the HII regions in our galaxy's nearest neighbors, the Large and Small Magellanic Clouds. Several investigations (1-7) have been addressed to this problem. In these endeavors one employs the measured intensities of the pertinent emission lines to get the temperature and density of the ionized nebular plasma as well as the concentrations of various individual ions, with respect to ionized hydrogen, e.g. $n(\text{N}^+)/n(\text{H}^+)$, $n(\text{O}^+)/n(\text{H}^+)$, etc. Perhaps the most uncertain step in the estimation of elemental abundances is to extrapolate from $n(\text{E}^i)/n(\text{H}^+)$ for the i th stage of ionization of an element E, to the total abundance ratio, $n(\text{E})/n(\text{H})$. In most investigations this step has been taken by empirical procedures, ultimately based in principle on concepts set forth by Bowen and Wyse (8).

Another approach is to use theoretical models for HII regions. We postulate a spherically symmetrical cloud of gas of assigned chemical composition surrounding a hot star whose emergent energy flux is presumed known. The density distribution of the gas as a function of distance from the star is also taken as an input parameter. One must know the atomic coefficients for photoionization and for collisional and radiative excitation of discrete levels, and one must take into account processes such as both ordinary and dielectronic recombination and charge

exchange. One then calculates the radiation field, the changing pattern of excitation and ionization, and emissivities in spectral lines as a function of distance from the central star. The program gives the spectral line emission integrated over the nebula, for each transition of interest; it also gives the fraction of atoms of each relevant element in each of its ionization stages. Intensities of forbidden lines depend not only on the ionic concentration but also on the electron temperature, which in turn is fixed by energy balance considerations (9).

Thus, one adjusts the available parameters—density distribution, ultraviolet flux of radiation from the illuminating star, and the chemical composition—in an effort to reproduce the observed line intensities. There are several disadvantages in the model nebular method. There exists no means of allowing for inhomogeneities and geometrical irregularities so characteristic of real nebulae. Furthermore, we have to employ theoretical model atmospheres to calculate the stellar energy distribution shortward of the Lyman limit. The model atmosphere and hence the predicted radiative flux depends on the assumed chemical composition of the illuminating star. An iterative procedure would involve fitting the radii, densities etc. of models to individual nebulae, deriving a preliminary chemical composition from a traditional analysis of the nebular spectrum, and then calculating a new stellar model atmosphere and flux distribution as a basis for a new family of models. Such an elaborate attack on the problem would be time consuming and expensive. In their analysis of HII regions in the spiral galaxy M101, Searle and Shields (10) have considered the influence of stellar chemical composition on emergent flux. Unfortunately, we do not know to what extent theoretical energy distributions are to be trusted in the far ultraviolet.

We did not attempt to construct detailed models of the two dozen emission nebulosities we have studied in the Magellanic Clouds; in fact, many are irregular in appearance. Instead we took chemical compositions derived from earlier analyses (3) and used them to calculate a network of nebular models for electron densities $N_e = 30 \text{ cm}^{-3}$ and 100 cm^{-3} and with stellar energy distributions with effective temperatures between 35,000 K and 40,000 K. We used Balick's (11) nebular model program, modified to take into account some additional ions, new atomic parameters, and charge exchange and dielectronic recombination. The theoretical stellar energy distributions are from Kurucz's (12) ATLAS program, supplied by him. They assume plane-parallel atmospheres of solar composition in local thermodynamic equilibrium.

It is to be emphasized that the predicted nebular spectra are very sensitive to the ultraviolet energy distributions; e.g., the stellar fluxes employed by Balick and Sneden (13) predict much lower excitation nebulae than those we obtain with ATLAS

Abbreviations: LMC, Large Magellanic Cloud; SMC, Small Magellanic Cloud.

Table 1. Derived abundances for HII regions in the Large Magellanic Cloud

Element	log [N(element)/N(H)] + 12.00 for nebulosities									
	N8	N11B	N11C	N44B	N44C	N44D	D51C	N55	N57	N59
N	7.05	7.00	6.83	7.13	7.10	6.88	6.85	6.94	6.95	6.83
O	8.42	8.34	8.22	8.30	8.39	8.48	8.42	8.47	8.53	8.44
Ne	7.75	7.50	7.61	7.95	7.99	7.57	7.80	7.51	7.72	8.01
(S)	6.96	6.80	6.63	7.00	6.90	6.62	6.42	6.93	6.33	6.76
Ar	6.42	6.20	6.13	6.26	5.85	6.58	—	—	6.62	7.30
Element	N79	N105A	N119	N120	N144	N158C	N159A	N160A	N160C	Mean
N	6.84	7.02	7.00	7.13	6.95	6.99	7.21	7.03	7.14	7.02
O	8.42	8.62	8.33	8.45	8.59	8.27	8.45	8.45	8.52	8.43
Ne	7.68	—	7.60	7.49	8.09	7.62	7.76	7.68	7.83	7.77
(S)	6.65	7.26	6.59	6.73	6.81	6.60	6.80	6.76	6.92	6.90
Ar	6.58	6.54	6.65	6.40	6.33	6.15	6.29	6.26	6.38	6.35

models of the same effective temperature. Our network of models nicely covered the range of excitation exhibited by the HII regions in our previous survey of the Magellanic Clouds (4). We used the $\lambda 3727[\text{OII}]/\lambda 5007[\text{OIII}]$ ratio to identify (or interpolate) the appropriate model. Then we could reproduce the intensities of [NII], [OII], [OIII], [SIII], and [ArIII] lines with nitrogen, oxygen, sulfur, and argon abundances not differing very much from those gotten by conventional methods. The predicted intensity of $\lambda 3868$ [NeIII] tended to be too low. Raising the neon abundance to fit the observed intensity would tend to disturb the energy balance in such a way as to weaken the agreement for the lines of the other ions. In other words, with present theoretical stellar flux distributions, the nebular models fail for the [NeIII] lines.

Accordingly, we decided to try another attack—i.e., to use the models as interpolation devices. First, we employed the surface brightness or $\lambda 6717[\text{SII}]/\lambda 6731[\text{SII}]$ ratio to choose an appropriate density. Then, within the network of models we would employ the $\lambda 3727/\lambda 5007$ ratio to establish the level of excitation. Whenever possible, we determined the electron temperatures from the $\lambda 4363/\lambda 5007$ ratio of [OIII]. With the electron density and temperature chosen, we then used conventional formulae to derive ionic concentrations from forbidden line intensities—i.e., $n(\text{N}^+)/n(\text{H}^+)$, etc. At this point the interpolated nebular model was invoked to obtain the fractional ionizations of N^+ , O^+ , etc.: $X(\text{N}^+)$, $X(\text{O}^+)$, etc. Then, for any element, E, we find the elemental abundance, $N(\text{E})/n(\text{H}) = N(\text{E}_i)/X(\text{E}_i)n(\text{H}^+)$. We employed this method previously (4) to obtain abundances of sulfur and argon.

Table 1 gives the derived abundances for HII regions in the Large Magellanic Cloud (LMC), while Table 2 gives similar data for the Small Magellanic Cloud (SMC). The last column gives the weighted mean. In comparing these results with those obtained previously (4), note that the new S^+ collision strengths given by Pradhan (14) lead to ionic concentrations about 25% lower than those found with his earlier approximation. We have not repeated the sulfur concentrations computed with the

Czyzak-Krueger cross sections because they were already given in tables 4 and 5 of ref. 4. The corrected argon results are given in the last row. Comparing these results with those previously given, note that the oxygen results are the same, because $[n(\text{O}^+) + n(\text{O}^{2+})]/n(\text{H}^+) \simeq n(\text{O})/n(\text{H})$. The nitrogen abundance is slightly lower, while that of neon is raised. The effects are not large.

Table 3 compares our present results with those of Dufour (5), Dufour and Harlow (6), and the Peimberts (1, 2) for the Magellanic Clouds, with the Peimberts' results for the Orion Nebula (a galactic HII region) (15), and with the sun. Except for neon, the solar abundances are taken from a review article by Ross and Aller (16). The solar neon abundance is poorly determined; large discordances exist between the extreme ultraviolet region results and those found from the solar x-rays of OVIII and NeIV by Acton *et al.* (17). The adopted value is close to that given by the Lockheed group (17).

The solar composition does not differ greatly from that of the Orion Nebula, considering the uncertainties in the analysis. There can be no doubt that nitrogen is deficient by about a factor of 5–8 in the LMC as compared with the Orion Nebula or the sun, but it is down by a factor of more than an order of magnitude in the SMC. Oxygen is depleted by a factor of 2 or 3 in the LMC but by about a factor of 5 in the SMC. The depletion of neon is small in the LMC (probably less than a factor of about 2); possibly it is depleted by a factor of about 4 in the SMC. The sulfur abundance is reduced by a factor of 2 with respect to the sun in the LMC and by a half an order of magnitude or more in the SMC. The depletion of argon is much less severe.

Table 4 compares our results with those of Pagel *et al.* (7) in the format employed in their paper. The discordance between the SMC sets of measurements amounting to a logarithmic average $|\bar{\Delta}| = 0.16$ is partly to be attributed to different methods of analysis, which lead to higher neon abundances by model procedures and otherwise to lower abundances. A much more important cause of discordance is that we were restricted to a small telescope (0.91-m aperture) for nearly all of our observations of the SMC. The data obtained by Pagel *et al.* (7) with the Anglo-Australian (4-m aperture) telescope are obviously superior. Nevertheless similar trends are well established. For the LMC, where the HII regions are mostly brighter, the results are in much better accord, $|\bar{\Delta}| = 0.07$.

Although the agreement between the various determinations is encouraging, there remains the challenge of obtaining more accurate abundances. Aside from inaccuracies in atomic constants and difficulties of modelling with geometrically irregular objects, there remain questions imposed by the density and temperature fluctuations.

Table 2. Derived abundances for HII regions in the Small Magellanic Cloud

Element	log [N(element)/N(H)] + 12.00						Mean
	NGC 346	N12B	N78	N83	N84	N90	
N	6.45	6.37	6.27	6.54	6.39	6.46	6.45
O	8.09	8.20	7.88	8.03	8.24	8.06	8.10
Ne	7.60			7.32	7.60	7.50	7.58
(S)	6.25	6.23		6.24	6.58		6.29
Ar	5.85	5.52		5.81	6.03	6.10	5.86

Table 3. Chemical compositions of Magellanic Clouds, Orion Nebula, and the sun

Element	$\log [N(\text{element})/N(\text{H})] + 12.00$							Sun, refs. 16, 17
	LMC			SMC			Orion Nebula, ref. 15	
	Present results	Ref. 5	Ref. 1	Present results	Ref. 6	Ref. 2		
N	7.02	6.80	7.10	6.45	6.48	6.48	7.76	7.94 ± 0.15
O	8.43	8.43	8.58	8.10	8.02	8.05	8.75	8.84 ± 0.07
Ne	7.77	7.64	7.94	7.58	7.29	7.30	7.90	8.1:
S	6.90	7.15		6.29	6.4		7.41	7.2 ± 0.15
Ar	6.35	7.10		5.86			6.7	6.0 ± 0.2

Substantial temperature fluctuations would require corrections to abundances found on the assumption of an isothermal nebular plasma (18). We have no direct evidence for such temperature fluctuations in the HII regions of the Magellanic Clouds, but the Orion Nebula in our own galaxy has been extensively studied. From measurements of the H66 α recombination line with a spatial resolution of 40", Pauls and Wilson (19) found an electron temperature of 8300 ± 300 K, which can be compared with a temperature of about 8500 K from the [OIII] lines (15) and a value of 8500 K from the radiofrequency continuum measurements by Shaver (20). We appear justified in adopting the isothermal approximation.

To what extent can the HII region compositions be taken as representative of that of the stuff from which stars are presumably formed at the present time? Analyses of atmospheres of supergiant stars usually suggested that metals are depleted in the LMC with respect to the sun (20–22), but the analyses sometimes gave solar abundances (23, 24). From an analysis of SMC supergiant star HR 7583, Przybylski (25) found an approximately "normal" helium abundance but a metal deficiency of about a factor of 10.

Analyses of old, massive supernova remnants which comprise material of the interstellar medium that has been bulldozed and shocked by a stellar explosion also indicate deficiencies of nitrogen and sulfur similar to those shown by the HII regions (26, 27).

Chemical composition analyses of planetary nebulae in the Magellanic Clouds have been carried out by various observers (28–30). Webster (31) concluded that the helium abundances in planetary nebulae are primordial, that the O/H ratio is that of the interstellar medium from which the parent stars were formed, but that the N/H ratio in these planetaries often exceeds that found in the HII region because nitrogen is generated in the stars themselves. These nitrogen-rich planetaries are often among the brightest objects and therefore they constitute favorite objects for study. We cannot be sure that the helium abundance has not been likewise affected, but the planetary nebular abundances of neon, sulfur, and argon are probably

truly representative of the interstellar medium. In planetary nebulae, grain formation ties up some elements, although the O/H ratio does not seem to be greatly affected. In harmony with Pagel *et al.* (7), we believe that the abundance ratios of N/H, O/H, and S/H are not much affected by grain formation in the HII regions and are thus primordial.

Abundance differences in both clouds have been attributed to differing rates of star formation in these systems, and theoretical models have been constructed by various groups to predict the rate at which galactic chemical compositions change. Pagel *et al.* (7) have made a critical examination of this matter as it applies to the Magellanic Clouds and nearby spirals M33 and M101. Their careful analysis shows that the amount of mass that experiences explosive nucleosynthesis (32) and is ejected in one stellar generation is very small compared to the amount tied up in white dwarfs, neutron stars, and long-lived stars. They find support for a simple hypothesis proposed by Audouze and Tinsley (33) for enrichment of heavy elements in galactic chemical evolution and that the rate of building up of these elements in the interstellar media of the Magellanic Clouds is similar to what is found in the outer region of Sc galaxies.

Although improvements in abundance determinations in HII regions in galaxies are approaching the point where they can lead to definitive tests of a nucleosynthesis hypothesis, severe limitations still remain. Aside from the inescapable difficulties imposed by irregularities in nebular structures, uncertainties in stellar flux distributions, and atomic parameters, there remains the question of how much material is tied up in grains and molecules such as CO and H₂. Data for some important elements, particularly carbon and silicon, are missing. We believe that carbon is less abundant than oxygen in the Magellanic Clouds, but a determination of $n(\text{C})/n(\text{H})$ must await data obtained with equipment such as the International Ultraviolet Explorer. Further infrared observations of the HII regions in the clouds are needed. In the next approximation, the HII regions of the Magellanic Clouds and of other galaxies should be modeled with stellar energy distributions appropriate to O and B stars of the same chemical composition.

Table 4. Comparison of abundance ratios

	O/H	O/N	O/Ne	O/S	O/Ar
SMC					
Ref. 7	7.98	1.57	0.82	1.6	2.04:
Model	8.10	1.65	0.52	1.81	2.25
$\Delta(\text{Ref. 7} - \text{model})$	-0.12	-0.08	± 0.30	-0.21	-0.21
LMC					
Ref. 7	8.39	1.51	0.78	1.6	2.04
Model	8.43	1.41	0.66	1.53	2.08
$\Delta(\text{Ref. 7} - \text{model})$	-0.04	+0.10	+0.12	+0.07	-0.04

The tabulated quantities are logarithms of abundance ratios.

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