
The Galactic Abundance Gradient

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Introduction

The study of chemical abundances and their variation from one galaxy to another or within individual galaxies is of fundamental importance for our understanding of the evolution of galaxies. The abundances of heavy elements in the interstellar medium provide a fossil record of the enrichment which has taken place due to nucleosynthesis in successive generations of stars. Gradients of heavy element abundances with distance from the galactic centre are predicted by models in which the rate of star formation varies across the galactic disk, and by dynamical collapse models of galactic evolution which involve fresh infall of primordial gas onto the disk over long periods of time. Different models predict different abundance gradients (in slope and shape), and abundance measurements give constraints on these models (see Pagel and Edmunds, 1981, Ann. Rev. Astron. Astrophys. 19, 77, for a recent review).

H II regions provide the most accessible probe of current interstellar abundances. In computing abundances from line intensity ratios, an accurate knowledge of the electron temperature is essential: a 40 per cent change in the temperature can change the abundance by an order of magnitude. Optically, temperatures can only be measured for the brightest and hottest H II regions, and this severely limits the number of H II regions for which "absolute" abundances can be determined.

Radio recombination lines can be used to obtain accurate electron temperatures for a much larger number of galactic H II regions. They are strongest when the temperature-sensitive optical lines are weakest, i.e. at low temperatures. In addition, they can readily be detected from relatively faint or heavily reddened H II regions. Thus the radio and optical methods are truly complementary. By carefully choosing the radio recombination lines to be observed in accordance with the emission measures of the H II regions, non-LTE corrections can be kept down to a few per cent, and uncertainties in the resulting temperatures are then limited only by observational factors, typically 5-10 per cent.

We have combined radio and optical spectroscopic observations of a large number of galactic H II regions in a novel approach to the determination of abundances and their distribution across the galactic disk. Accurate temperatures have been measured for 67 H II regions located between 3.5 and 13.7 kpc from the galactic centre; optical spectra have been obtained for 32 of these H II regions, bringing the total number of galactic H II regions with known (absolute) abundances from 18 to 43.

Some Preliminary Results

The radio observations were made using the 210-foot radio telescope at Parkes in Australia. Sample spectra, showing the 108 lines of hydrogen and helium, and the 137 line of hydrogen, are given in Fig. 1. These lines arise from transitions in the extreme outer parts of the atoms: the 108 line is due to a n = 110 → 109 transition (n = principal quantum number), and the 137 line is due to a n = 139 → 137 transition. Of special interest in Fig. 1 is the narrowness of some of these lines, proving that some H II regions have electron temperatures below 5,000 K (= 15 km s-1).

Optical spectra were obtained using the Image Dissector Scanner (IDS) and the Image Photon Counting System (IPCS) on the ESO 3.6-m telescope, and with the IPCS at the Anglo-Australian Telescope. Fig. 2 shows a representative selection of these spectra. Variations in excitation conditions, temperature, and abundances are revealed by changes in the [O III]/Hβ.
and [N II]/Hβ ratios. The strong reddening evident in the bottom three spectra highlights the difficulty in finding candidates for optical observations in the important region within 7 kpc of the galactic centre.

The radio-determined electron temperatures, corrected for the small deviations from LTE, were applied to these optical spectra to compute abundances. At this point an additional uncertainty enters, related to possible stratification effects within each H II region: the temperatures of the O+, O++, N+, and H+ zones may differ significantly from each other. Photoionization models (such as those by Stasinska, 1980, Astron. Astrophys. 84, 320) suggest that such differences can be important especially below 7,000-8,000 K. Thus the derivation of abundances from optical spectra using radio temperatures is to some extent model-dependent, and the uncertainty is greatest at low temperatures (and therefore in the inner regions of the galaxy).

Fig. 3 shows the electron temperatures (from the radio data), the He++/H+ ratios (from radio and optical data), and preliminary oxygen and nitrogen abundances (from the radio temperatures, the optical spectra, and one set of models), plotted against galactocentric distance. Gradients are clearly present in T_e, O/H, and N/H, but not in He++/H+.

The T_e and O/H gradients are mutually consistent, on the assumption that oxygen is the prime coolant in H II regions. On the other hand, the range of temperatures at a fixed R_g is due in large part to the range of effective temperatures of the exciting stars and to the range of densities of the H II regions: most of this spread is real, and not due to observational error.

The absence of any significant gradient in He++/H+ may be due to two effects which roughly balance each other. The total helium abundance may increase with metallicity, i.e. towards the galactic centre, due to helium production in stars. On the other hand the increasing metallicity may reduce the relative number of helium-ionizing photons, and therefore the He++/H+ ratio, due to line blanketing in the stellar atmospheres.

Finally, the similarity of the oxygen and nitrogen abundance gradients is surprising, because these are thought to be primary and secondary nucleosynthesis products respectively. Primary elements have 1H or 4He as their direct progenitors, whereas secondary species are formed by subsequent processing of a primary element. Thus, the abundance of a secondary element should increase as the square of the abundance of its primary progenitor. Most metals do vary in
lockstep with oxygen, as expected for primary elements. The
fact that the nitrogen abundance gradient is not much steeper
too steep suggests that much of the nitrogen may also be of primary
origin. A further puzzle arises in the fact that several isotopic
ratios ($^{16}$O/$^{18}$O, $^{13}$C/$^{12}$C, $^{34}$S/$^{32}$S, $^{15}$N/$^{14}$N, etc.), measured at millime-
ter wavelengths, are constant to a high degree over the plane of
the galaxy, in apparent contradiction to the marked gradients in
18, 399). These facts seem to call for a revision of our ideas
about nucleosynthesis.

It is thought that the disk of our galaxy formed gradually, with
infall of primordial gas extending over a long period. The main
evidence for this is the shortage of old stars in the disk with low
abundances. These infall models share the prediction that the
abundance gradient should flatten off in the inner regions of the disk
(Tinsley and Larson, 1978, Astrophys. J. 221, 554; Chiosi,
1980, Astron. Astrophys. 83, 206). There is no evidence for this
in Fig. 3, but there are a number of ways out of this dilemma,
such as postulating infall of metal-enriched gas from stars in the
galactic bulge. There are clearly many free parameters in
such models, but an increasing array of observational data will
hopefully provide the constraints necessary to ultimately dis-
sum the actual evolutionary scenario.

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Fig. 3: Variations of electron temperature and preliminary abundance
ratios $^{16}$O/$^{18}$O, O/H, and N/H, as a function of distance from the galactic
centre. Arrows to the right indicate values for the LMC (30 Doradus)
and SMC (N66).