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EXAMINATION OF SYSTEMATIC ERRORS IN ABUNDANCES DERIVED FROM NEBULAR SPECTRA

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RESUMEN

Examinamos la validez global de la metodología típica para inferir las abundancias de los elementos a partir de los espectros de las regiones H II. Se construyó una red the modelos de densidad constante para obtener un conjunto de los "factores de corrección"(i_{CF}s) requeridos. Aplicamos éstos a las abundancias iónicas de los modelos de densidad constante derivados de espectros sintéticos, así como a modelos de bordes angostos exponenciales y modelos de nudos individuales brillantes. La comparación entre las abundancias elementales usadas en los modelos y las que se infieren de los i_{CF}s muestran grandes desviaciones respecto a la exactitud esperada del procedimiento de análisis. Estas inexactitudes siguen distintas tendencias entre los tres modelos, lo que sugiere que no hay una solución sencilla aplicable para cualquier nebulosa.

ABSTRACT

We examine the global accuracy of the typical methodology for inferring elemental abundances from H II region spectra. A grid of constant-density models is constructed and used to build a suite of the required "ionization correction factors" (i_{CF}s). We apply these to the ionic abundances of the constant-density models inferred from their synthetic spectra, as well as models with narrow exponential edges and models of individual bright knots. Comparison of the elemental abundances used in the models to those inferred from the i_{CF}s show deviations large with respect to the expected accuracy of the analysis procedure. These inaccuracies follow different trends among the three models, suggesting no simple fix useful for arbitrary nebulae.

Key Words: **H II REGIONS — ISM: ABUNDANCES**

1. INTRODUCTION

The abundances of elements within H II regions are largely determined by analysis of their optical emission-line spectra. Their optical spectra are usually relatively simple, comprised of a handful of strong and one or two dozen weak emission lines on top of a continuum of nebular and reflected (or direct) starlight. If the density and temperature within a region of the nebula can be established, the flux of a given emission line can be translated into an abundance of the corresponding ion within that region. The abundances of an element's ionic stages can then be used to determine the abundance of that element.

Two complications arise when trying to determine abundances with this approach. First is the necessity of imposing a simple ionization structure to interpret the spectra. In general the ions for which bright lines appear in the spectra are grouped into one of two zones according to the ionization potentials of the ions. The physical conditions used to infer the ionic abundances in each zone are held constant, determined from densities and temperatures inferred from diagnostic ratios of lines appearing in the spectra. In contrast, theory and models show that a given ionic species in an H II region spans a region with both density and temperature gradients, and is rarely co-spatial with other ions.

Second, not all of the populous ionic stages of an element have bright optical lines; N^{2+}, for example. These unseen stages are compensated for through the use of "ionization correction factors" (i_{CF}s). Introduced in Peimbert & Costero (1969). these were initially based on coincidences in ionization potential between two ionic stages and assuming similar fractional abundances for those ionic stages; e.g., $N^+/N = O^+/O$. Advances in computing have made it possible to replace these empirical formulae with grids based on the ionization fractions within a large suite of model nebulae, enumerated with respect to some set of observable abundances. Although presumably more accurate, these model-based i_{CF}s carry with them other simplifications – namely, that observed nebulae have similar structure to the model grids, which are almost always constant density. This study examines the cumulative effects of the two-zone methodology for determining ionic abundances and model-based i_{CF}s on the inferred elemental abundances in H II regions.

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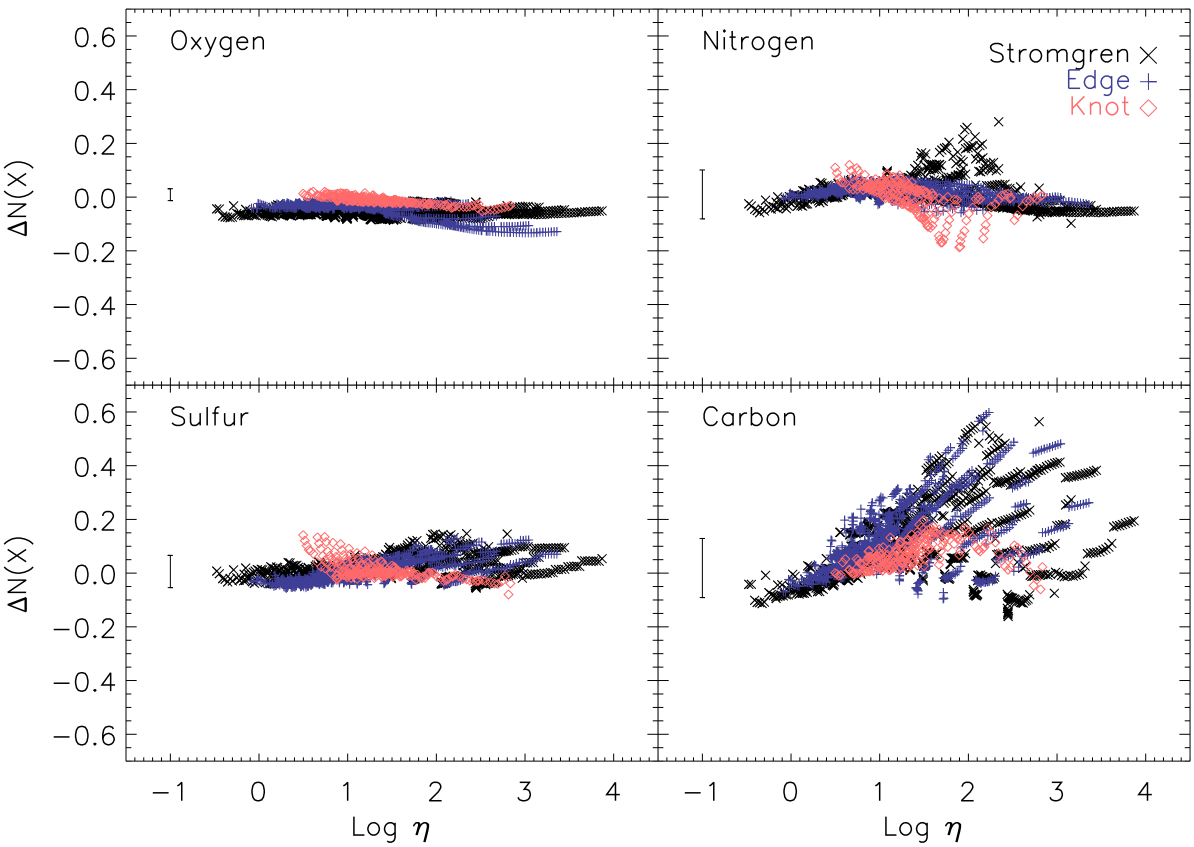

Fig. 1. Abundance errors for oxygen, nitrogen, sulfur, and carbon. The logarithmic errors in each element for each model are plotted against $\log \eta = \log[O^+/O^{2+}] - \log[S^+/S^{2+}]$, as determined from their spectra.

2. THE I$_{CF}$ GRID AND MODEL NEBULAE

The i$_{CF}$ grid was produced by creating from a large grid of Strömgren models using the photoionization code *Cloudy 94* (Ferland 1998). Each model is ionized by a single star powering the nebula, chosen from a suite of models of main-sequence stars presented in Aufdenberg (2000) and provided by the author, over a range of effective temperatures from 32 to 51 kK. The total ionizing flux from the star Q_0 ranged from 10^{47} to 10^{54} photons per second, in steps of 0.1 dex. The model nebulae had hydrogen densities of 100 cm^{-3}, and were assumed to be ionization-limited; i.e., all ionizing photons from the star are absorbed by the surrounding gas. We use a single set of elemental abundances in the model grid, the *Cloudy 94* default values for H II regions. The model fractional abundance for each ion of interest was then extrapolated from the model results with respect to O^+/O^{2+} and S^+/S^{2+}.

The synthetic spectra for the models in the i$_{CF}$ grid were interpreted using the two-zone methodology, in a manner similar to that given in Shaw & Dufour 1995. From the optical and near-IR part of the synthetic spectrum we infer abundances for the following ions: O^+, O^{2+}, S^+, S^{2+}, N^+, He^+, Cl^{2+}, Ne^{2+}, and Ar^{2+}. Although none of its important ionic stages have bright optical lines, the carbon abundance is also of astrophysical interest; so we infer an abundance for C^{2+} from the 1909 Å UV lines. For these ions the singly-ionized species are assigned to the low-ionization zone, and the doubly-ionized species to the medium-ionzation zone. The intrinsic error in using our code on *Cloudy 94* line strengths varies among the ions, but is of order 0.02 dex. We note that this also affects the i$_{CF}$ value used, so the total errors differ between each element. With the exception of oxygen, whose abundance is determined simply as $O = O^+ + O^{2+}$, the ionic abundances are translated into elemental abundances using the corresponding i$_{CF}$s.

To study the effects of different density structures on the results, we also examined the spectra of two alternate models. The first of these was a nebula

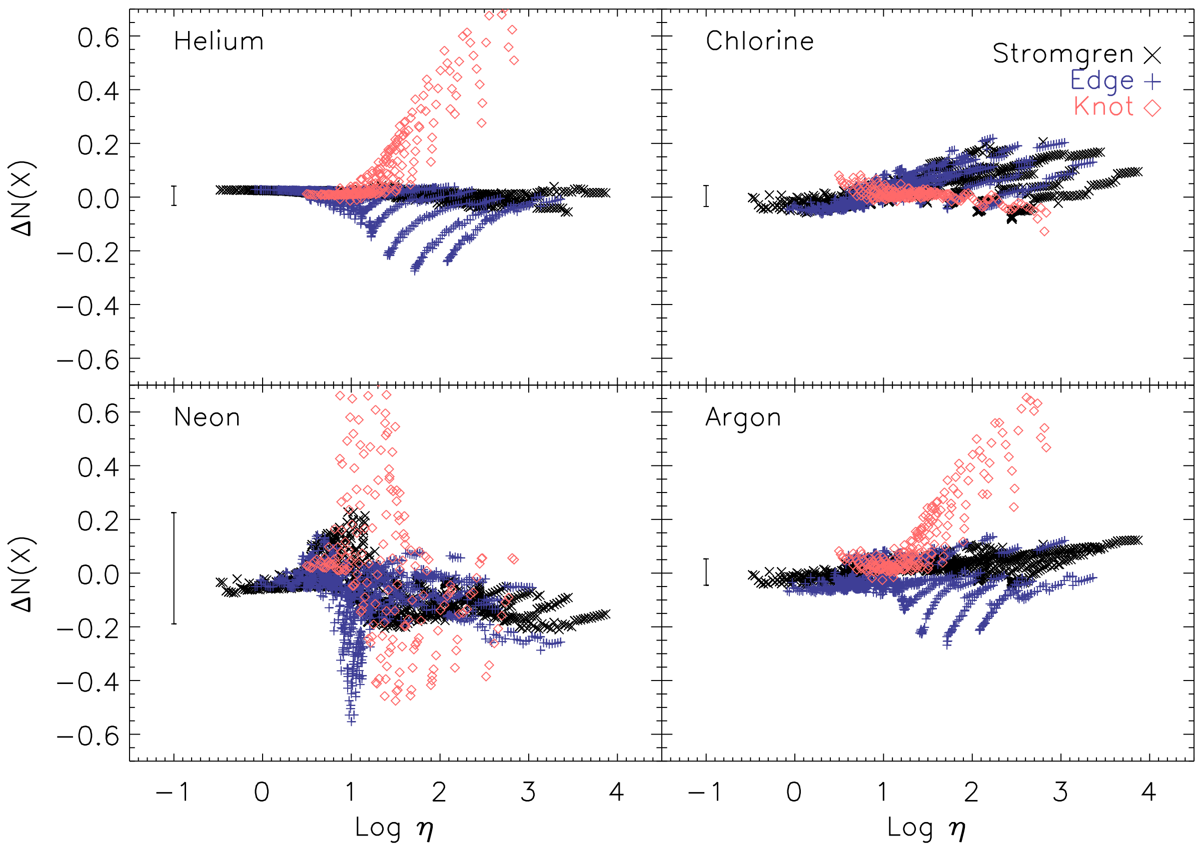

Fig. 2. Abundance errors for helium, chlorine, neon, and argon. The logarithmic errors in each element for each model are plotted against $\log\eta = \log[O^+/O^{2+}] - \log[S^+/S^{2+}]$, as determined from their spectra.

with constant density out to one-half the Strömgren radius, where a sharp exponential rise takes place. The scale height of this "blister"-type model was chosen to give a density of approximately 1000 cm^{-3} at the ionization limit. The parameters for the central star were identical to those in the Strömgren model grid. The second alternate model was for an ionized knot one parsec from the central star. This was modeled as a sharp ($\sigma = 10^{16}$ cm) gaussian with a peak density of 1000 cm^{-3}. The ionizing fluxes ranged from 10^{48} to $10^{49.5}$ in steps of 0.1 dex, the lower limit of which is sufficient to ionize the knot just to its peak density. Their spectra were interpreted as before, and total abundances inferred from the i_{CF}s produced for the Strömgren models.

3. RESULTS AND DISCUSSION

The results for the three models are shown in Figures 1 and 2 plotting the errors (in dex) against $\log\eta = \log[O^+/O^{2+}] - \log[S^+/S^{2+}]$. Before considering the results we remind the reader of our demonstrably high accuracy, far higher than those quoted for actual observations. To show this standard to the reader we include in each graph an estimated range of errors for each element. This was determined by establishing the accuracy with which each ion could be determined from *Cloudy 94* spectra with our analysis code, as well as the propagation of that error through the i_{CF} grid. The range shown encompasses 99% of the deviations expected from this analysis. With this limit for each abundance determination no more than ten models should fall outside the range indicated.

The figures show that the results for all three model suites well exceed the expected range of errors. Not surprisingly the Strömgren models agree best of all, since they formed the basis of the i_{CF}s employed in the study, but the number of models in excess of the expected error is quite large. Put simply, the failures of those models show the effect of imposing the two-zone ionization structure; the inaccuracies in the blister and knot models illustrate the additional effect of an i_{CF} grid based on models with a significantly different mix of ionic species within them. The results for most elements show reasonable agreement for very low and high values of $\log \eta$; unfortunately, the observations of Galactic nebulae given in Rodriguez (1999) span the range of $\log \eta$ of 0.6 to 2.0, where the errors tend to peak. More importantly, the figures show that the trends in the errors with respect to $\log \eta$ differ among the models, implying that a simple global correction to the method is improbable. At a minimum, the large difference between the blister and knot model results demonstrates that an i_{CF} appropriate for the volume-integrated spectrum of a nebula is likely inapplicable to the spectra of resolved knots.

Based on this study, we caution against undue reliance on the i_{CF} methodology as it is now employed, and suggest that it be used only as an initial estimate for abundances used in building tailored models for observed nebulae or their resolved small-scale structure.

A more detailed account of this study is presented in Moore, Hester, and Dufour (2004).

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