TITLE
ASP Conference Series, Vol. **VOLUME***, **YEAR OF PUBLICATION**
NAMES OF EDITORS

On the Ionization of Heavy Elements in Diffuse Interstellar Clouds

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Abstract. We briefly discuss several puzzles related to the ionization of heavy elements in diffuse interstellar clouds — in our Galaxy and in the SMC.

1. Introduction

It is commonly assumed that photoionization and radiative recombination dominate the ionization equilibrium of heavy elements in diffuse interstellar clouds: $\Gamma\ n(\mathrm{X\ I}) = \alpha\ n_e\ n(\mathrm{X\ II})$, where Γ is the photoionization rate, α is the recombination rate, and n_e is the electron density. Recent observational and theoretical studies have suggested, however, that additional processes may often play a significant role. For example, the electron densities inferred from the ratios $N(\mathrm{X\ I})/N(\mathrm{X\ II})$, for different elements X, can differ by more than an order of magnitude along a given line of sight, if photoionization equilibrium is assumed. Moreover, the patterns of relative n_e observed in different lines of sight show both similarities and differences — suggesting that multiple additional processes besides photoionization and radiative recombination significantly affect the ionization balance of heavy elements — to different degrees in different lines of sight. Where independent estimates can be made for both n_e and the local hydrogen density (n_{H}), the resulting fractional ionization is often much greater than the value $2{\times}10^{-4}$ that would be expected if most of the electrons come from ionization of carbon and other heavy elements.

2. Relative Electron Densities from X I/X II

Several recent studies have suggested that the ratios $N(\mathrm{X\ I})/N(\mathrm{X\ II})$, for different elements X but for the same assumed T and radiation field, can yield markedly different values for n_e (HD 215733, Fitzpatrick & Spitzer 1997; 23 Ori, Welty et al. 1999). For the highest column density clouds toward 23 Ori, the average n_e derived independently from nine pairs of neutral and singly ionized species range over a factor $\sim$ 20. We have estimated n_e for the main interstellar clouds toward 23 Ori and four other stars, based on high-resolution optical and UV (*HST*/GHRS) spectra (Welty, Hobbs, & Morton 2002). Figure 1 shows those n_e, relative to the respective averages (n_0) of the values for C, Na, and K; n_e/n_0 should be fairly insensitive to the actual values of T and the ambient radiation fields characterizing the clouds in the different lines of sight.

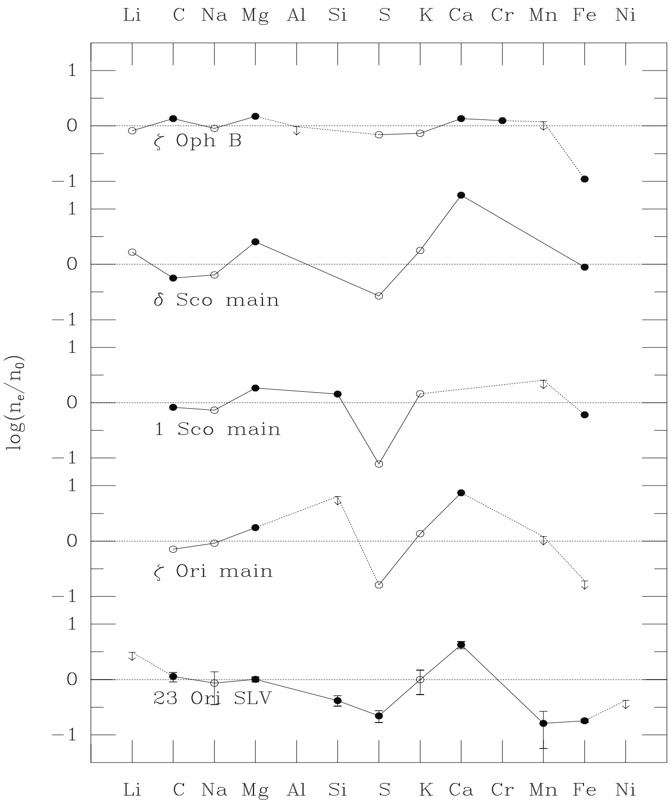

Figure 1. Logarithm of relative electron density (n_e/n_0) for the main components toward five stars. Open circles denote cases where N(X II) was estimated based on N(Zn II) and typical depletions; representative 1 σ error bars are shown for 23 Ori. Note the similarities between 23 Ori and ζ Ori, and between 1 Sco and δ Sco — and the differences between those two pairs and ζ Oph. The points for S, Mn, Fe, and Ni are often low; Ca is often high.

Figure 1 shows that the differences in relative n_e found toward 23 Ori are neither unique nor universal. The n_e inferred for the main clouds toward ζ Ori, for example, are significantly lower than those toward 23 Ori, but show a very similar pattern — with roughly similar values from C, Na, Mg, and K, low values from S and Fe, and a high value from Ca. The patterns seen toward 1 Sco and δ Sco are also similar, except that the n_e derived from Si and Fe are comparable to the values derived from C, Na, Mg, and K — rather than much lower, as seen toward 23 Ori. In the main clouds toward ζ Oph, however, most elements — even S and Ca — give very similar n_e, and only Fe gives a low value.

The differences in the element-to-element pattern of relative n_e for these five lines of sight suggest that the differences in n_e inferred for any given line of sight are not just due to a single process or factor — but instead result from multiple additional processes that selectively affect the ionization balance of the various elements, to different degrees in the different lines of sight. Lepp et al. (1988), Fitzpatrick & Spitzer (1997), Welty et al. (1999), Weingartner & Draine (2001), and Welty et al. (2002) all have discussed some possible factors and/or processes: incorrect f-values for individual transitions, errors in the photoionization and/or recombination rates, differences in the shape of the radiation field, dielectronic recombination (increasing Ca I and Mg I in warm gas), dependence of depletion on local hydrogen density, dissociative recombination of CH^+ (increasing C I), charge exchange between singly ionized species and large molecules / small grains (enhancing the corresponding neutral species), and charge exchange with protons (reducing some of the trace neutral species). While some of these processes may have some effect, none appears able to account for all the apparent differences in inferred n_e.

3. Fractional Ionization

The other puzzling aspect of the ionization balance in the main clouds toward 23 Ori is the apparently high fractional ionization: $n_e/n_{\rm H} \sim 0.01$. This is a factor ~ 50 higher than the value $\sim 2{\times}10^{-4}$ expected from photoionization of carbon and other abundant heavy elements, and a factor ~ 10 higher than the values obtained by including ionization of H and He due to cosmic rays and x-rays (e.g., Wolfire et al. 1995; Weingartner & Draine 2001). Similar estimates for $n_e/n_{\rm H}$ in the main clouds in eight other sightlines (in Orion, Sco-Oph, and Cepheus) reveal several other cases where $n_e/n_{\rm H}$ is clearly higher than the value expected from photoionization of heavy elements alone (Welty et al. 2002). After accounting for (probably) elevated radiation fields in the Sco-Oph region, it is possible that most of the clouds in this small sample have $n_e/n_{\rm H}$ significantly in excess of $2{\times}10^{-4}$; there may be a range in $n_e/n_{\rm H}$ of more than a factor of 10. The apparently high fractional ionization could imply either that n_e has been overestimated (e.g., if charge exchange processes are important) or that hydrogen is slightly ionized even in predominantly neutral gas — or both.

4. Main SMC Clouds toward Sk 155

Studies of the interstellar medium (ISM) in the Magellanic Clouds (MC) explore somewhat different environmental conditions (metallicity, dust-to-gas ratio, ambient radiation field, UV extinction) than those typically probed in our own Galactic ISM. Determination of elemental abundances, depletions, and physical conditions in the MC ISM therefore provides interesting tests for theoretical models of both interstellar clouds and interstellar dust grains.

Using high-resolution (FWHM $\sim$ 1.4 km s^{-1}) Na I spectra, STIS echelle spectra (FWHM $\sim$ 2.7 km s^{-1}), and *FUSE* spectra (FWHM $\sim$ 25 km s^{-1}), we have begun to address these issues in the various interstellar clouds toward the SMC star Sk 155 (Welty et al. 2001 and in prep.). The STIS spectra have revealed unusual relative abundances/depletions in several of the main SMC components — severe depletions for Cr, Fe, and Ni but negligible depletions for Mg and Si — a pattern which has not been seen in the Galactic ISM. Analysis of the C I fine-structure excitation, for several of the main SMC components, indicates thermal pressures $n_{\rm H}T$ of about $10^{3.9-4.1}$ cm^{-3}K. Such pressures are higher than those typically found in our Galaxy (Jenkins & Tripp 2001), but are consistent with predictions for lower metallicity gas (e.g., Wolfire et al. 1995). Using $T_{01}(\mathrm{H_2}) \sim 85$ K, the n_{H} range from about 80–150 cm^{-3} in the two main SMC components. If we assume typical depletions for C and Na, and that the radiation field is 5 times the Galactic WJ1 field (e.g., Lequeux 1989), then we estimate $n_e \sim 0.02$–0.10 cm^{-3} in several of the main SMC components. The corresponding values estimated from $N(\mathrm{Mg\,I})/N(\mathrm{Mg\,II})$ are factors of 2–6 higher — comparable to some of the discrepancies seen in our Galaxy (Fig. 1). The fractional ionization in those SMC components thus ranges from about 0.00020 to 0.00125 — factors of $\sim$ 5–30 higher than the value $\sim 4{\times}10^{-5}$ "expected" (for the lower metallicity SMC) if the electrons come from ionization of carbon and other heavy elements. Again, such differences are comparable to those found locally.

5. Summary / Conclusions

Estimates of n_e and n_{H} based on the assumptions of photoionization equilibrium and $n_e/n_{\mathrm{H}} \sim 2{\times}10^{-4}$ must be considered to be very uncertain — particularly if they are based on only a single ratio $N(\mathrm{X\,I})/N(\mathrm{X\,II})$. Observations of lines from many different neutral/first ion pairs, for additional sightlines sampling different environmental conditions, may help us to understand the various processes affecting the ionization balance in diffuse clouds. High-resolution UV spectra of faint targets (e.g., heavily reddened Galactic stars and stars in the Magellanic Clouds) will be very useful.

Acknowledgments. Support for this work has been provided by NASA LTSA grant NAG5-3228; by NASA grants GO-2251.01-87A and GO-08145.01-A from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS5-26555; and by NASA grant NAG5-10370 (FUSE).

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