Photoionization rates in the interstellar medium*

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Summary. New photoionization rates, calculated using the radiation field of Gondhalekar, Phillips & Wilson, are presented for several species of importance in the interstellar medium. These results are compared with the previous estimates of de Boer, Koppenaal & Pottasch.

1 Introduction

The photoionization rate $\Gamma$ of an atom or ion is an important quantity in the analysis of interstellar clouds, as it can be used to estimate electron densities through the well-known ionization–recombination equation (see, for example Spitzer 1978)

$$N_e = \frac{\Gamma N(X^i)}{\alpha N(X^{i+1})}$$

where $N(X^i)/N(X^{i+1})$ is the ratio of the densities of $X$ in the $i$th and $(i + 1)$th ionization stages (which may be equated to the ratio of the column densities assuming the same linear distribution of $X^i$ and $X^{i+1}$ along the line-of-sight), $\alpha$ is the total recombination coefficient of $X^{i+1}$ and $\Gamma$ is the photoionization rate of $X^i$. (It should be noted that this equation only holds for a purely photoionized gas as it ignores potentially important processes such as collisional and Auger ionization.) Several elements have measurable column densities in more than one stage of ionization and may be usefully employed as electron density diagnostics, e.g. calcium (White 1973; Federman & Hobbs 1983), chlorine (Jura & York 1978), manganese (Cardelli & Bohm-Vitense 1982), magnesium (York 1983) and carbon and sulphur (Morton 1975). Alternatively, a knowledge of $N_e$ allows the amount of an element present in unobservable states such as Na II and Ca III to be estimated and this is important in depletion studies (see, for example Morton 1975).

De Boer, Koppenaal & Pottasch (1973) have determined photoionization rates for many species using the interstellar radiation field of Witt & Johnson (1973). Unfortunately the latter only performed calculations for wavelengths down to 1250 Å, which is above the photoionization threshold for several elements (for example S I), so that accurate determinations of their rates could not be made. However, more recently Gondhalekar, Phillips &

* Dedicated to the memory of Mary F. Bogues.
Wilson (1980) have redetermined the radiation field from 2740 Å down to the Lyman limit at 912 Å using improved galactic model calculations, and found it to be considerably smaller than the Witt & Johnson estimate. This is due mainly to the different observational data employed, Witt & Johnson using OAO-2 stellar observations in their galactic model and the results of Witt & Lillie (1972) for the albedo of the interstellar grains. Gondhalekar et al. on the other hand used photometric data obtained from the S2/68 sky-survey telescope and the grain albedos of Morgan, Nandy & Thompson (1978). In this paper new photoionization rates are presented that have been calculated using the Gondhalekar et al. results.

2 Results and discussion

Numerically the photoionization rate in H I regions may be expressed as

\[
\Gamma (s^{-1}) = 5.04 \times 10^{-11} \int_{912 \AA}^{\lambda_0} \sigma_\lambda F_\lambda \lambda d\lambda
\]

where \( \sigma_\lambda \) (Mb) is the photoionization cross-section at wavelength \( \lambda \) (Å), \( F_\lambda \) (erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\)) the radiation field taken from Gondhalekar et al. (1980), and \( \lambda_0 \) the threshold wavelength for photoionization. In Table 1 the present results are summarized for several species of importance in the interstellar medium, along with the sources of the cross-section data. The latter have been collected from the literature, and in general should be more reliable than

<table>
<thead>
<tr>
<th>Species</th>
<th>Threshold (Å)</th>
<th>( \Gamma ) (de Boer et al.)</th>
<th>( \Gamma ) (present work)</th>
<th>Reference</th>
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<tr>
<td>C I</td>
<td>1102</td>
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<td>3.6–11†</td>
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<td>1.7–9</td>
<td>5</td>
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</tr>
</tbody>
</table>

* 2.3–10 implies 2.3 \times 10^{-10}.
† Taken from Phillips, Gondhalekar & Blades (1981).

References

1. Cantu et al. (1981)
2. Laughlin (1978)
4. Le Dourneuf et al. (1975)
5. Chapman & Henry (1972)
6. McGuire (1968)
7. Dill, Starace & Manson (1975)
10. Sandner et al. (1981)
13. Tondello (1975)
14. Hansen et al. (1977)
15. Lombardi, Smith & Parkinson (1978)
those used by de Boer et al. (1973), as they represent the most recently published theoretical and experimental determinations. Also given in Table 1 are the photoionization rates calculated by de Boer et al. using the radiation field of Witt & Johnson (1973). These are an average of their $\Gamma(WJ1)$ and $\Gamma(WJ2)$ results, where $\Gamma(WJ1)$ was deduced by assuming that the Witt & Johnson field decreased linearly to zero at 912 Å, and $\Gamma(WJ2)$ by taking the field to be constant between 1200 and 912 Å. For the sake of completeness, the recent calculation of $\Gamma(Mg I)$ by Phillips, Gondhalekar & Blades (1981) using the Gondhalekar et al. radiation field is quoted in the table.

From Table 1 it may be seen that the present results are in general smaller than the de Boer et al. (1973) values, sometimes by more than a factor of 2. This is probably due to differences in the Gondhalekar et al. and Witt & Johnson radiation fields, although in the case of Al I the different cross-section data used is responsible for the increase in the photoionization rate. The new calculations will tend to decrease the electron densities previously derived in the literature, and should also affect some depletion factors.

Most of the $\Gamma$ values listed in Table 1 should be accurate to approximately 50 per cent. However, as de Boer et al. (1973) noted, interstellar H$_2$ molecules may cause extra absorption at wavelengths shorter than 1100 Å. Considerable amounts of H$_2$ are known to exist in interstellar space (see Savage et al. 1977) and hence species with photoionization thresholds $\lambda_0 \leq 1100$ Å, such as C I and Ca II, may have unreliable rates due to uncertainties in the radiation field. More generally, it should also be noted that large variations in the radiation field will occur in regions of space near OB associations or within dense dust clouds, with corresponding effects on the photoionization rates (see, for example Jura 1974; Spitzer & Morton 1976).

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References