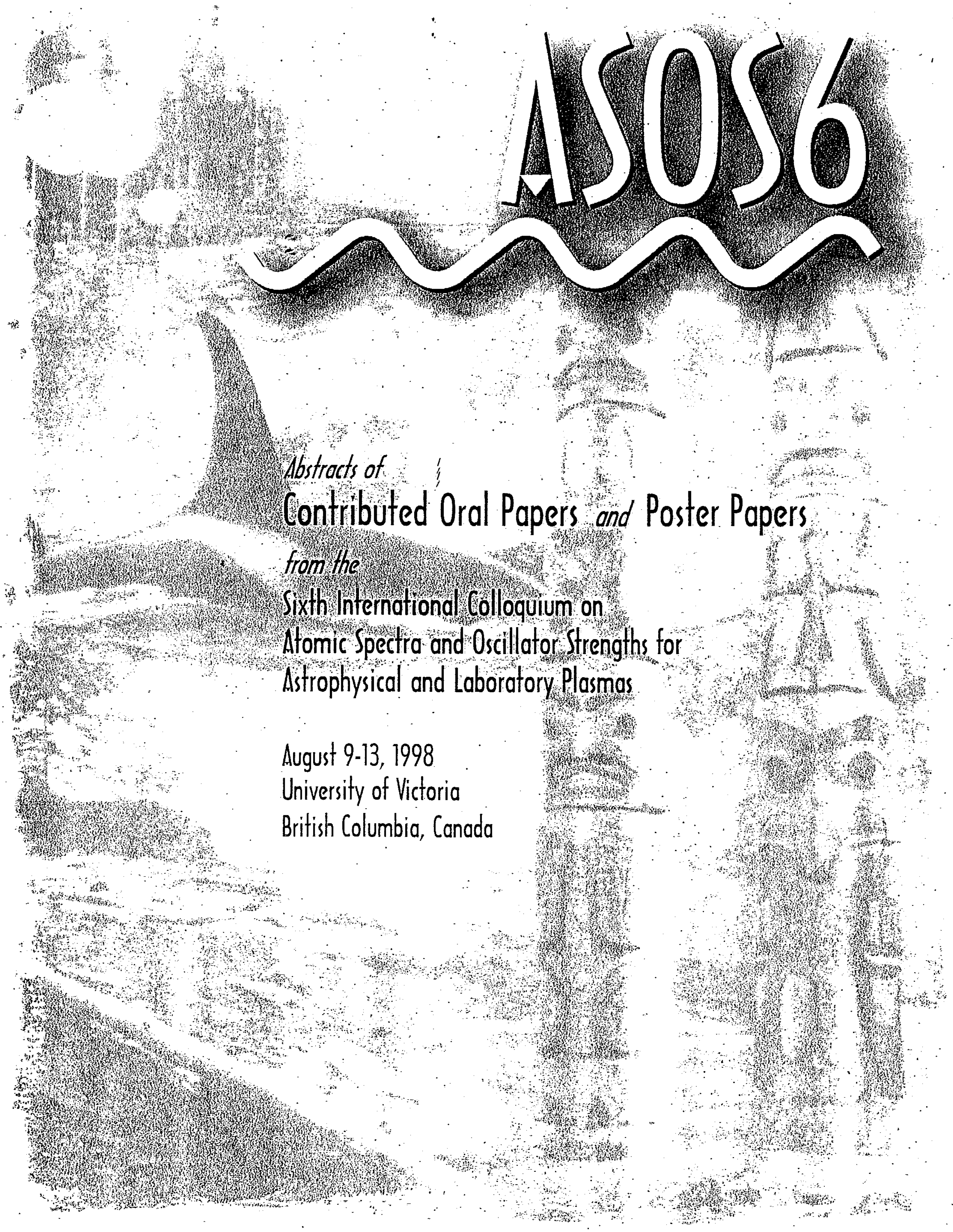

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PHOTOIONIZATION AND RECOMBINATION OF IONS AND ATOMS

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1. Introduction

In radiatively ionized plasmas ionization equilibrium is maintained by the inverse processes of photoionization and recombination. Employing a new method for unified, total electron-ion recombination, we present comprehensive and self-consistent sets of photoionization cross sections, σ_{PI}, and total recombination rate coefficients, α_R, for astrophysically abundant atoms and ions. The self-consistency is attained by using identical eigenfunction expansions in the close coupling calculations for both the quantities. This reduces the uncertainties introduced by using different approximations, valid in different energy ranges, considered heretofore.

In our previous works (e.g. Nahar 1995,1996a), the calculations were done mainly along iso-electronic sequences. Some calculations were also done for important systems such as S II-III, and Si I-II (Nahar 1995, 1996a). For applications, such as full ionization balance calculations, all ionization stages of a given element, i.e., along an iso-nuclear sequence, must be considered since the ionic fractions depend on coupled ionization stages. We have obtained photoinization cross sections and total recombination rate coefficients of C, N, and O through all ionization stages, and the ionization fractions in plasmas in coronal equilibrium (Nahar and Pradhan 1997, Nahar 1998, 1999).

In addition to the total photoionization and recombination data, state-specific cross sections are also obtained for a large number of excited states for Non-LTE models. Complete datasets are available electronically.

Under the Iron Project (IP) (Hummer *et al.* 1993) large scale computations are being carried out for the radiative data for the iron ions, e.g., for Fe I (Bautista 1997), Fe II (Nahar and Pradhan 1994), Fe III (Nahar 1996b), Fe IV (Bautista and Pradhan 1997), and Fe V (Bautista 1996). Concurrently, the unified treatment is also being employed for these heavy ions to calculate the total recombination rate coefficients, e.g., for Fe I (Nahar *et al.* 1997), Fe II (Nahar 1997), Fe III (Nahar 1996c), Fe IV (Nahar *et al.* 1998), and Fe V (Nahar and Bautista 1999). These have been the first detailed calculations for these heavy ions.

2. Theory and Computations

Calculations for photoionization and recombination are carried out in the close coupling approximation using the R-matrix method. The photoionization cross sections, σ_{PI}, are obtained including the autoionizing resonances as in the Opacity Project (OP) (Seaton 1987). Most of the photoionization cross sections obtained are new, and improved over the OP. They are obtained using larger and more accurate wavefunctions to ensure proper inclusion of the correlation effects.

The calculations of total electron-ion recombination employs a new unified treatment (Nahar and Pradhan 1994, 1995, Nahar 1996c). The method considers the infinite number of recombining states and incorporates the radiative and dielectronic recombinations, RR and DR, in a unified manner. The contributions to recombination from states with $n \leq 10.$ are obtained from σ_{PI} using detailed balance, while the resonant contributions from $10 < n \leq \infty$ are obtained from the DR theory of Bell and Seaton (1985).

Determination of ionization fractions in a plasma involves a set of coupled equations requiring recombination rates for all ionization stages (e.g. Nahar and Pradhan 1997). Present total recombination rates for C, N, O ions are applied to compute ionization fractions in coronal or collisional equilibrium between electron impact ionization and electron-ion recombination.

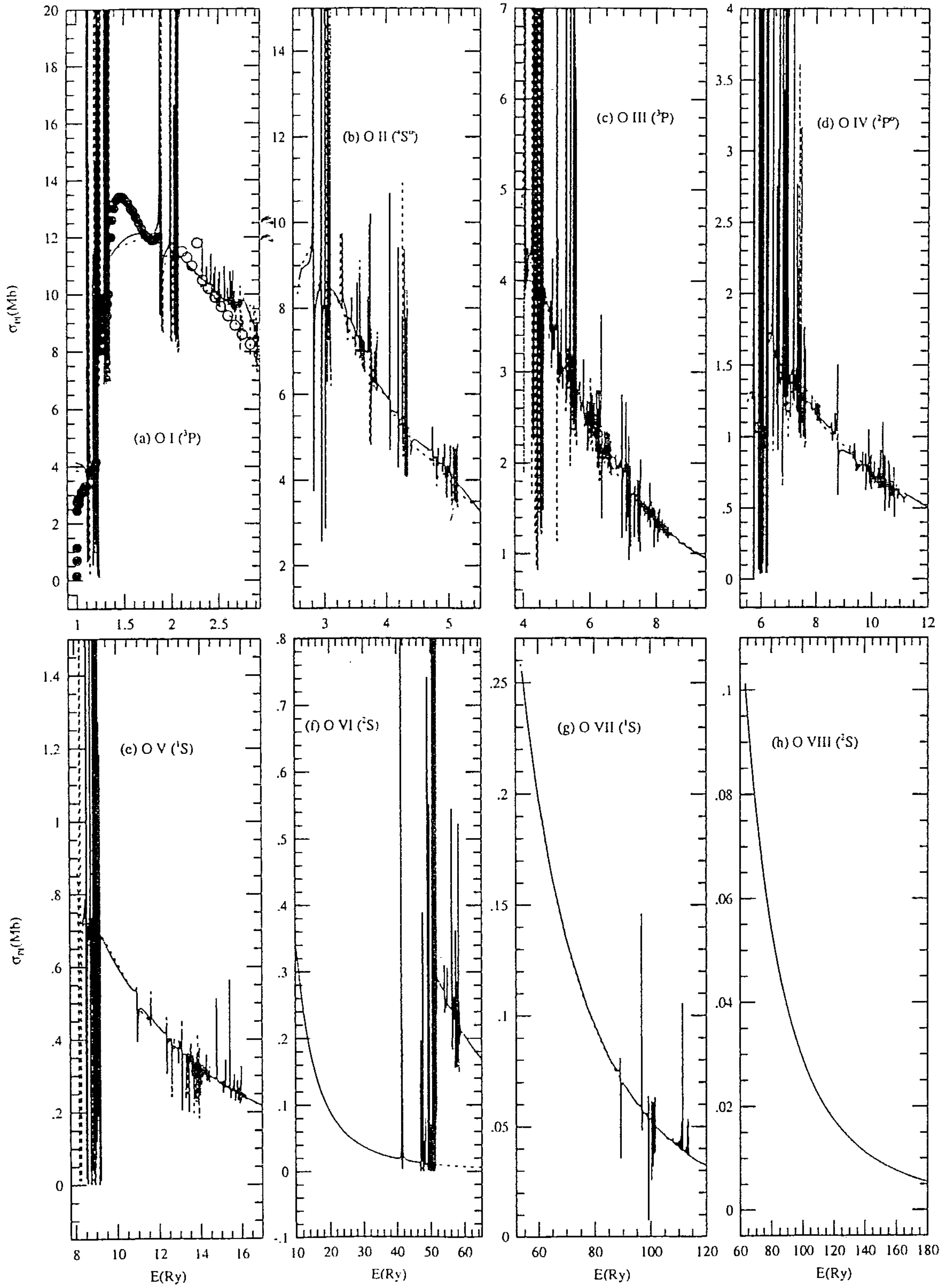

Fig. 1.— Photoionization cross sections of oxygen ions.

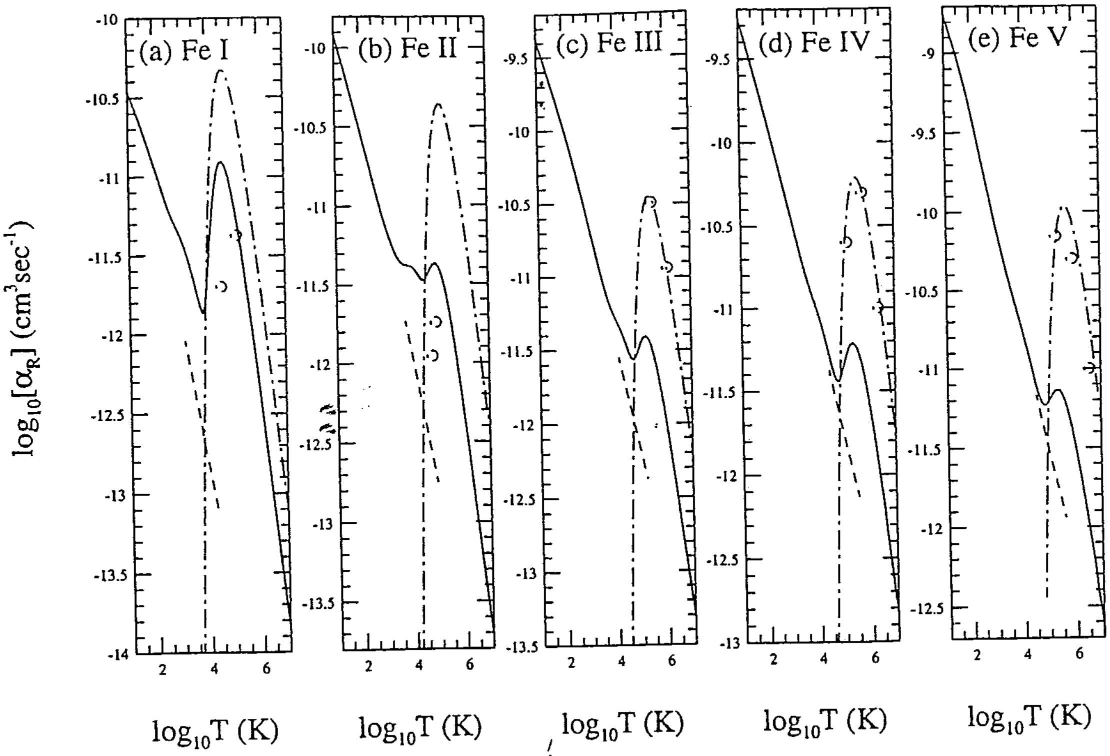

Fig. 2.— Recombination rate coefficients of Fe ions.

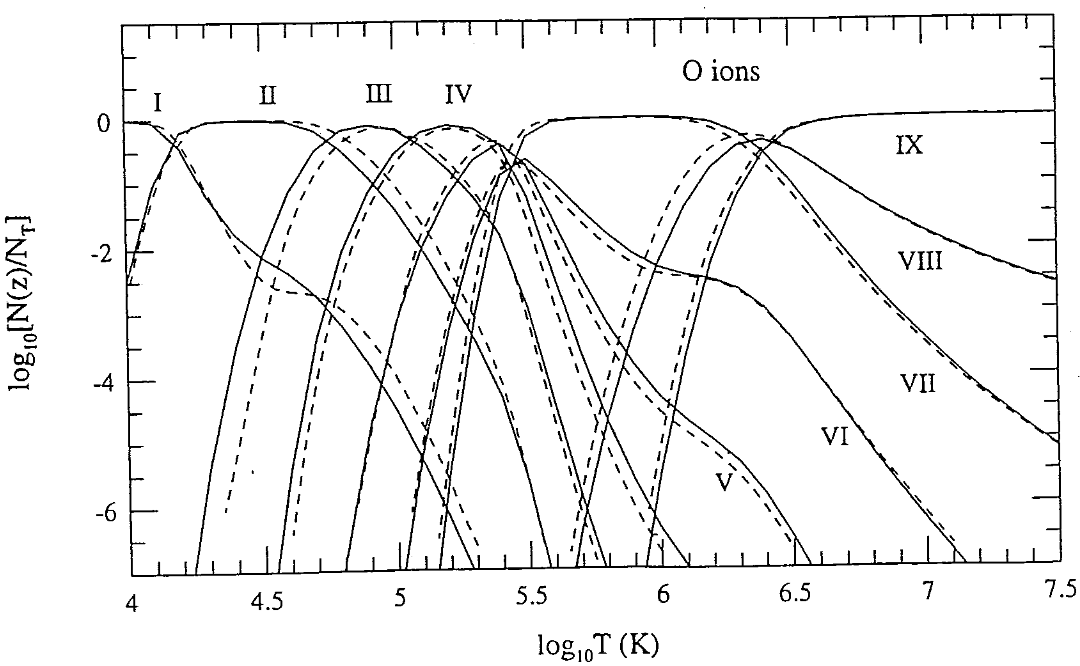

Fig. 3.— Ionization fractions of oxygen ions.

3. Results

We present samples of results for σ_{PI}, $\alpha_R(T)$, and ionization fractions, N_i/N_T, in a collisionally ionized plasma.

Figure 1 presents σ_{PI} of the ground states of oxygen ions, O I - O VIII; the solid curves are present values, dotted ones are from the OP, and the circles are the experimental values. The comparison with experiment is explained in Nahar (1998).

Total recombination rate coefficients, $\alpha_R(T)$, for Fe I - Fe V (solid curves) are presented in Figure 2. Other curves are from earlier calculations using simple approximations for RR and DR (details are given in the references). Considerable differences can be noticed between the present unified and the sum of the earlier (RR+DR) results. Compared with the earlier results it may be seen that autoionizations to excited levels in the high temperature region reduce the recombination rates significantly.

Figure 3 presents oxygen ionization fractions (solid curves) in a plasma in coronal equilibrium (Nahar 1999), and compares with the earlier values by Sutherland and Dopita (1993) (dashed curves). Although the basic features in the two sets of values are similar, significant differences also exist, e.g. the depth of the 'dip', and the high temperature behaviour of O I. Significant differences are seen in several other cases, such as for O II, O III and O VIII, at temperatures when the ionic abundance is comparatively high. These differences could affect the computation of ionization balance and spectral line intensities in astrophysical models.

4. Acknowledgements

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