



Collisional dissociation cross sections for O + O₂, CO and N₂, O₂ + O₂, N + N₂, and N₂ + N₂

R.E. Johnson*, M. Liu, C. Tully

Engineering Physics Program and Astronomy Department, University of Virginia, Charlottesville, VA 22904-4745, USA

Received 7 February 2001; accepted 21 May 2001

Abstract

Using laboratory data for the scattering of O by O₂, CO and N₂ pair potentials are constructed for O, C and N atoms. These potentials are then used to calculate collisional dissociation and energy transfer cross sections for O on O₂, CO and N₂, O₂ on O₂, N on N₂, and N₂ on N₂. Since the energetic ions often neutralize in the atmosphere corona, such cross sections are relevant to plasma ion bombardment of the atmospheres of Mars, Titan, Triton and Europa. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

The flow of the solar wind plasma, a plasma trapped in a planetary magnetic field or a local pick-up ion plasma onto the exobase of an atmosphere produces chemistry, heating and atmospheric loss. These processes, which can affect the evolution of an atmosphere, are often referred to as atmospheric sputtering. When the atmosphere near the exobase is atomic, both Monte Carlo descriptions (e.g., Johnson et al., 2000) and analytic models (e.g., Johnson, 1990, 1994) of the collision cascades initiated by the incident ions are available. When measured atomic collision cross sections are not available for such calculations, scaled potential functions have been used to describe collisional ejection.

Atmospheres on a number of small planetary bodies have been shown to have molecules at the exobase and in the corona: SO₂ at Io (Wong and Johnson, 1996), CO₂ at Callisto (Carlson, 1999) and Mars (Bougher et al., 1999), O₂ at Europa and Ganymede (Hall et al., 1995, 1998), N₂ at Titan (Yelle et al., 1997) and Triton (Cruikshank et al., 1993). In such cases, atmospheric sputtering calculations using a fully dissociated atmosphere can be used to roughly estimate the loss (Johnson et al., 2000; Johnson and Luhmann, 1998). In addition, if whole molecules are the principal ejecta, simple collision cross sections can be used (Pospieszalska and Johnson, 1996). Monte Carlo atmospheric models which correctly treat collisions that allow molecular dissociation are not only more complicated, but in the energy range of

interest (~a few keV to ~ 20 eV) the required cross sections are typically not available. Since the incident ions often neutralize well above the exobase, the energetic particles are often neutrals. There are essentially no laboratory data for collisional dissociation of relevant molecules by energetic neutrals.

In response to a Monte Carlo description of sputtering of Mars' atmosphere (Kass and Yung, 1995), we calculated collisional dissociation cross sections for energetic O, CO and CO₂ on CO₂ using classical molecular dynamics and scaled pair potentials (Johnson and Liu, 1998). In the work described here, we extract semi-empirical potentials from laboratory scattering data and use them to calculate collisional energy transfer by energetic O to O₂, N₂ and CO. That is, we use laboratory data on the scattering of energetic O atoms by molecules to construct pair potentials between the incident and target atoms. Then we use these potentials to calculate the energy transfer and collisional dissociation cross sections. We also scale these results to estimate the N + N₂ and N₂ + N₂ cross sections needed at Titan. In this paper, we do not treat dissociation due to electronic processes. These begin to become important at higher energies and will be dealt with in the subsequent work. The calculated cross sections are compared to those calculated using the binary encounter model and their relevance for Europa and Titan are discussed.

2. Empirical potentials

Smith et al. (1996), Lindsay et al. (1998) and Schafer et al. (1987) have measured the angular differential scatter-

* Corresponding author. Tel.: +1-804-982-2335;
fax: +1-804-924-1353.

E-mail address: rej@virginia.edu (R.E. Johnson).

ing cross sections, $\sigma(\theta)$, for the atomic O on a number of molecules (O_2 , N_2 , CO and CO_2) in the energy range 0.5–5 keV. These are presented as ρ vs. τ plots, where $\rho = \theta \sin\theta \sigma(\theta)$ and $\tau = E_0 \theta$ with E_0 and θ as the energy and scattering angle of the incident O. In this form, the data is nearly energy independent (e.g., Johnson, 1982). To obtain interaction potentials, we parameterize standard forms for pair potentials between the incident atom and the atoms in the molecules. These potentials are then used in a classical molecular dynamics program to calculate the scattering cross sections. The parameters for each potential form are adjusted to reproduce the ρ – τ data. By creating interaction potentials which reproduce the scattering data we are able to accurately determine the total energy transfer to the target molecule. Since the laboratory data do not give dissociation, we use the constructed potentials to calculate the energy transfer as well as to calculate dissociation cross sections.

In these calculations, a Morse potential

$$V(r) = D_e \{ \exp[-2\alpha(r - r_0)] - 2 \exp[-\alpha(r - r_0)] \}, \quad (2.1)$$

is used to describe the interaction between the atoms in the target molecule. Here, $D_e = 5.19$ eV, $\alpha = 2.958/\text{\AA}$ and $r_0 = 1.2$ \AA for O_2 and $D_e = 9.8$ eV, $\alpha = 2.718/\text{\AA}$ and $r_0 = 1.1$ \AA for N_2 . For the N_2 target, both accurate ground state N_2 potential energy and the Morse potential were used and a comparison of the calculated dissociation cross sections was made. Although the Morse potential is not accurate near the dissociation limit, very little change (a few percent) occurred in the collisional dissociation cross section and in the effective threshold for dissociation when the accurate N_2 ground state potential was used. It was found that the dissociation cross section was primarily sensitive to the size of the dissociation energy and to the interaction potentials between the incident and target particles.

To describe the interaction of an O atom with the individual atoms of a diatomic molecule, a potential scaled to data can be used. For collisions between atoms with open shells there are a number of interaction potentials associated with the atomic ground states. Although these affect the trajectories in low energy collisions (Tully and Johnson, 2001), at the separations of primary interest here the interactions are repulsive. The so-called universal repulsive potential (Zeigler et al., 1985; hereafter the ZBL potential), which is obtained from a fit to scaled cross section data has been used to describe the interaction potentials for the atomic systems in this study. Here, we test it against the scattering data, using it as the pair potential between the incident atom and each atom in the molecule. The ZBL potential is given by

$$V_{ZBL}(r) = \frac{Z_A Z_B e^2}{r} \varphi(r/a_{ZBL}),$$

$$a_{ZBL} = 0.8853 a_0 / (Z_A^{0.23} + Z_B^{0.23}), \quad (2.2)$$

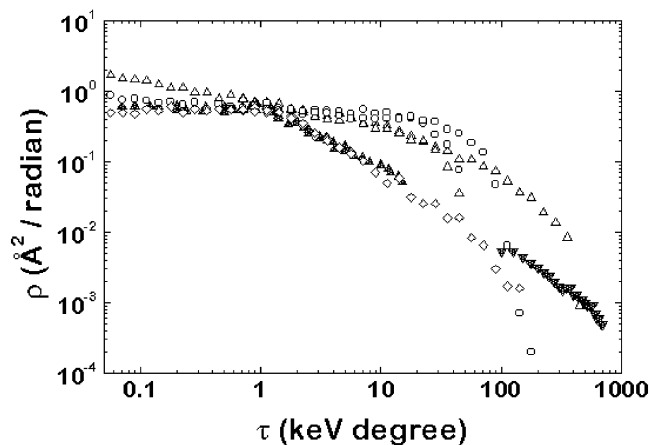


Fig. 1. ρ – τ plot for scattering of O from O_2 . Laboratory data: solid triangles (Schafer et al., 1987; Smith et al., 1996, at a number of energies, 0.5–5 keV) and Fuls et al. (1957) for energetic $Ne^+ + Ne$, solid inverted triangles. Calculations at two energies, 0.5 and 5 keV (results are nearly identical until the maximum energy transfer is reached): open circles, theory (Abrahamson, 1969); open triangles, ZBL potential (Zeigler et al., 1985); open diamonds our favored potential $[V_x^{-1} + V_n^{-1}]^{-1}$ where $n=2$ (Table 1). ($\rho = \theta \sin\theta \sigma(\theta)$, where θ is the laboratory scattering angle and $\sigma(\theta)$ is the laboratory scattering cross section and $\tau = E_0 \theta$, where E_0 is the incident atom energy.)

where

$$\varphi(x) = 0.181 \exp(-3.2x) + 0.5099 \exp(-0.9423x) \\ + 0.2802 \exp(-0.4029x) + 0.02817 \exp(-0.2016x), \quad (2.3)$$

a_0 is the Bohr radius and r is the internuclear separation. More recently, the individual potentials of Gartner and Hehl (1979) have been improved upon and used (J.F. Ziegler, private communication) having a form for φ like that of the above, but with different coefficients.

A simple exponential potential of the form

$$V_x(r) = A_x \exp(-r/a_x), \quad (2.4)$$

often called a Born–Mayer potential, is also examined. Such forms have been used for atom–atom collisions and as a pair potential for atom–molecule collisions (Macheret and Adamovich, 2000). It is first incorporated using parameters from Abrahamson (1969): $A_x = 1316.1$, 1709.9 and 2143.4 eV and $(a_x)^{-1} = 2.016$, 2.009 and 2.005 $(a_0)^{-1}$, respectively, for C + C, N + N and O + O. For the heteronuclear collisions, the form $V_{12} \approx (V_{11} V_{22})^{1/2}$ has been tested and is recommended. V_x has also been extracted from low energy data (Foreman et al., 1976). They give $A_x = 905$, 316 eV and $a_x = 3.856$, 3.221 \AA^{-1} for O+O and O+N. Finally, the Born–Mayer form is also used here with adjustable A_x and a_x to describe the data at small τ (large r).

In Fig. 1 is given ρ vs. τ calculated for O + O_2 using the ZBL potential and V_x from Abrahamson (1969) as pair potentials between the incident O and an O in the molecule. These are compared with the laboratory scattering data. It is observed that V_{ZBL} is not a very good description of the

interaction at any value of τ . Poor agreement with the data is also found for all the other collision pairs. Similar results are obtained using the individual potential for O + O, although the agreement at small τ is better. Similarly, reducing the screening constant for the V_{ZBL} (e.g., a_{ZBL} approaching 0.65 a_{ZBL}) improved the agreement for O + O₂ at small τ . The convenient ZBL form for the potential has been used in a number of calculations of atmospheric sputtering (e.g., Johnson and Liu, 1998). These are now being repeated with better potentials. The potential V_x calculated for atom–atom interactions is seen to give very good agreement at small τ (large r) when used as a pair potential for the O + O₂ collision, but fails dramatically at large τ .

To obtain more accurate interaction potentials we use analytical forms for the atom–atom pair potentials and fit the experimental data for the collisions of interest. Recently, Tully and Johnson (2001) calculated in detail low energy scattering of O with O. No separate experimental data exists for the atom–atom interactions in the energy range of interest. For scattering of O by O₂, CO and N₂, at large τ the dominant scattering mode is a binary collision of the incident atom with one of the atoms in the target, allowing the extraction of an effective atom–atom potential, $V(r)$. In this case the measured ρ is twice the size of ρ for the atom–atom interactions. Here, we roughly extend the range of the data at large τ for O + O by using the Ne⁺ + Ne data of Fuls et al. (1957).

If the atom–atom interaction potential is approximated by a repulsive power law

$$V_n(r) = \frac{C_n}{r^n} \quad (2.5)$$

then the reduced cross section variable ρ is given by (Johnson, 1982)

$$\rho \approx \frac{1}{n} \left(\frac{a_n C_n}{\tau} \right)^{2/n}, \quad (2.6)$$

where

$$a_n = (\pi)^{(1/2)} \frac{\Gamma[(n+1)/2]}{\Gamma(n/2)}, \quad (2.7)$$

and $\Gamma(x)$ is the gamma function. Therefore, values of n and C_n are easily extracted for a range of r (i.e., τ) (e.g., Fuls et al., 1957). At large τ , using half of the measured ρ for the collisions O + O₂ the power law coefficients C_n and n are determined for each value of τ . We find that a single value of n and C_n can represent the data above $\tau \sim 2$ keV deg. At large internuclear separations for O + O, the potential is nearly exponential (implying $n \rightarrow \infty$) and we use the form V_x above. The range of data available is well fit for ~ 0.1 – 1 Å using V_n and at $r \gtrsim 1.2$ Å by fitting A_x and a_x for V_x , $A_x = 2347.73$ eV and $a_x = 0.2$ Å, and combine these in the form $V(r) = [(V_n)^{-1} + (V_x)^{-1}]^{-1}$ as seen in Fig. 1.

These forms were also used to fit the data for O + N₂ and O + CO. The calculated ρ – τ fits to the laboratory data are equivalent to those seen in Fig. 1 for O + O₂, and the appropriate parameters for the pair potentials are summarized in Table 1. In order to construct the potentials for energetic

Table 1
Parameters for interaction potentials

Potential	$C_n(\text{eV} \cdot \text{Å}^n)[A_x(\text{eV})]$	$n[a_x(\text{Å})]$
O + O ₂		
(1). $[\frac{1}{V_n} + \frac{1}{V_u}]^{-1} V_n = \frac{C_n}{r}$	8.38	2
(2). $V_x = A_x \exp(-r/a_x)$	[2143.4]	[0.264]
(3). $[\frac{1}{V_n} + \frac{1}{V_x}]^{-1}$	[2347.7]	[0.2]
(4). V_n spline to V_x	[905.0]	[0.259]
O + N ₂		
$[\frac{1}{V_n} + \frac{1}{V_u}]^{-1}$	4.48	2.59
O + CO		
$[\frac{1}{V_n} + \frac{1}{V_u}]^{-1}$	4.44	2.68
O + O		
V_n spline to $V_x^{(4)}$		
O ₂ + O ₂		
$[\frac{1}{V_n} + \frac{1}{V_u}]^{-1}$	8.38	2
N + N ₂		
(5). $V_n = C_n/r^n$	2.465	3.301

(1) V_u : Universal (ZBL), Ziegler, J.F. et al. (1985). The stopping and range of ions in solids. Pergamon, New York.

(2) Abrahamson, A.A. (1969) Born–Mayer-type interatomic potential for neutral ground-state atoms with $Z = 2$ to 105, 178, 76–79.

(3) Our best fit of A_x and a_x .

(4) Foreman, B.P. et al. (1976) used for V_x Repulsive potentials for the interaction of oxygen atoms with the noble gases and atmospheric molecules 12, 213–224.

(5) Also used $[\frac{1}{V_n} + \frac{1}{V_u}]^{-1}$ using $C_n = 2.4$ eV Å^n , $n = 3.18$ obtained from above data using $V_{12} \approx [V_{11} \times V_{22}]^{1/2}$ and the new individual potential for V_u (Ziegler, J.F., personal communication). Resulting potential is close to power potential given.

N incident on N₂ we use the best power law potential extracted for O + O and O + N and the procedure described in Abrahamson (1969) for pair potentials to construct an N + N potential. This is used in calculations for N + N₂ and N₂ + N₂. We compare two cases. First, we use the power laws for O + O and O + N in Table 1 for large τ and combine with V_u for N + N using the parameters for the individual potential (Gartner and Hehl, 1979). We also use a single power law fit over the full range of τ for both O + O₂ and O + N₂ and obtain a simple power law potential for N + N. The resulting potentials are very similar.

3. Cross sections

Using the above pair potentials in a classical molecular dynamics calculation, the total energy transfer to the target molecule is calculated. The collisional dissociation cross section is then calculated. Dissociation occurs when the internal energy of the diatom after the collision exceeds the binding energy. For each initial molecular orientation and for each impact parameter this is examined after the collision. If the total energy between the atoms is negative the molecule remains intact, otherwise the diatom dissociates. The probability of dissociation, p_D , is obtained by counting the number of times the molecule dissociates for a single impact parameter and dividing by the number of molecular

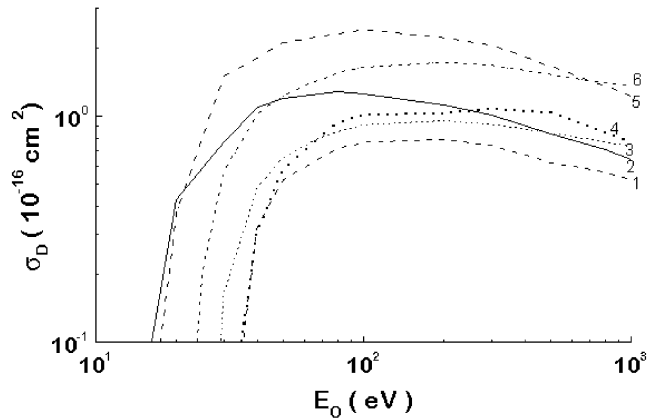


Fig. 2. Collisional dissociation cross sections vs. incident atom energy obtained from pair potentials in Table 1. 1. O+N₂, 2. O+O₂, 3. N+N₂, 4. O+CO, 5. O₂+O₂, and 6. N₂+N₂. Parameters of fits for these are given in Table 2.

Table 2

Parameters for fitting $\sigma_D[\sigma_D = C(E - E_t)^x / (A + E^y)]^a$

Parameters	O + O ₂	O + CO	O + N ₂	O ₂ + O ₂	N ₂ + N ₂	N + N ₂
<i>C</i>	4.51	4.69	2.75	8.53	3.01	3.38
<i>x</i>	1.03	1.34	0.96	1.42	1.11	1.73
<i>A</i>	0.21	9.96	2.25	2.06	0.749	1.16
<i>y</i>	1.31	1.58	1.18	1.68	1.20	1.53
<i>E_t</i>	14.5	29.0	29.0	14.5	19.9	24.9

^aEnergy is in eV; cross section is in 10⁻¹⁶ cm²; *E_t* is an effective ‘threshold’ here: $\sigma_D \rightarrow 0.05 - 0.1$.

orientations. This process is repeated for a large number of *b* to obtain the integrated cross sections, given by

$$\sigma_D = 2\pi \sum p_D b \Delta b, \quad (3.1)$$

where *p_D* is the probability of dissociation averaged over orientations.

Collisional dissociation cross sections are shown in Fig. 2 for O + O₂, O + CO, O + N₂, N + N₂, O₂ + O₂ and N₂ + N₂ using the parameters for the pair potentials in Table 1. As shown earlier for O + CO₂ collisions (Johnson and Liu, 1998), but not shown here, the oft-used binary encounter approximation is reasonably accurate above the steep rise in the cross section at low energy (the effective threshold) but poorly describes the effective threshold. This convenient model can also be used in the effective threshold region if a ‘dissociation energy’ (Sieveka and Johnson, 1984) fitted to the effective threshold in Fig. 2 is used. It is the transfer of energy to the target as a whole that results in a larger than expected effective threshold even accounting for the mass ratios. For the atom–molecule collisions calculated it is about three times the actual dissociation energy. Dissociation can occur down to the true threshold but is not accurately calculated by the model used here. Also shown are dissociation cross sections for collisions between molecular species. For use in atmospheric models, in Table 2 we present parameters for fits to these cross sections.

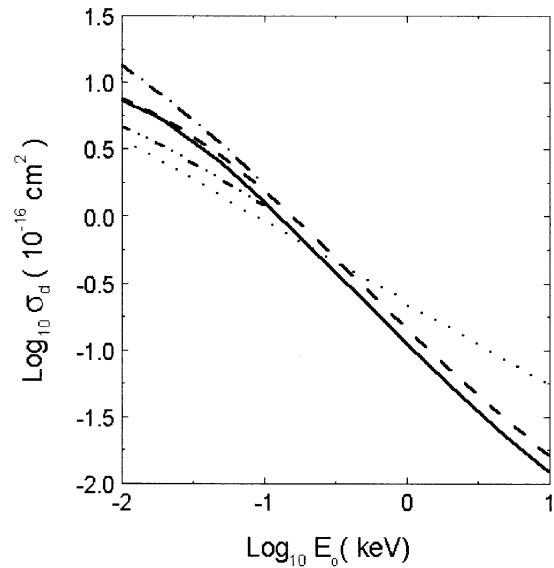


Fig. 3. Diffusion (momentum transfer) cross section, σ_d , calculated using the pair potentials in Table 2. O + O₂ (solid line), O₂ + O₂ (dash-dot), N + N₂ (dotted), and N₂ + N₂ (dash-dot-dot). O + O₂ (dashed line) using $S_n/[\gamma E_0/2]$ as discussed in the text.

In Fig. 3 results are given for σ_d , the diffusion (momentum transfer) cross section, for O+O₂, N+N₂, O₂+O₂ and N₂+N₂ again using the potentials in Table 1. These are the cross sections that control the escape of energetic particles from a molecular planetary atmosphere (Johnson, 1994). Therefore, these determine the exobase altitude, $\sim (n\sigma_d)^{-1}$. For collisions in which energy is lost to internal degrees of freedom, the momentum transfer cross section is $\sigma_d = \int \int (1 - f \cos \chi) b \, db \, d\phi$, where χ is the center of mass scattering angle and ϕ is the azimuthal angle. This is then averaged over molecular orientations as above. Here, *f* is the ratio of the center of mass momentum after the collision to that before the collision, which is unity when there is no energy lost to internal degrees of freedom. Also shown for O + O₂ is $S_n/(\gamma E_0/2)$, where *S_n* is the energy transfer cross section and γE_0 is the maximum energy transfer in a head-on collision for point particles, $\gamma = 4M_A M_B / (M_A + M_B)^2$, where *M_A* and *M_B* are the masses of the incident and target particles. This is exactly equal to σ_d for the collision of two atoms with no internal degrees of freedom. For collision of an atom with a diatom it is slightly larger than σ_d . In analytical models of the sputtering of atmospheres (Johnson, 1994), the ratio $S_n(E_0)/[U\sigma_d(U)]$, where *U* is the gravitational binding energy and *E₀* is the incident ion energy, roughly determines the number of molecules ejected per ion incident.

It is also seen that the dependence of σ_d on *E₀* is somewhat different for nitrogen than oxygen. Often the same potential parameters are used for both O₂ and N₂. Since the nitrogen potentials were obtained by a less direct method we will carry out a much more detailed set of calculations for this system in the future using the full set of ground state potentials, as we did earlier for O + O. The results for

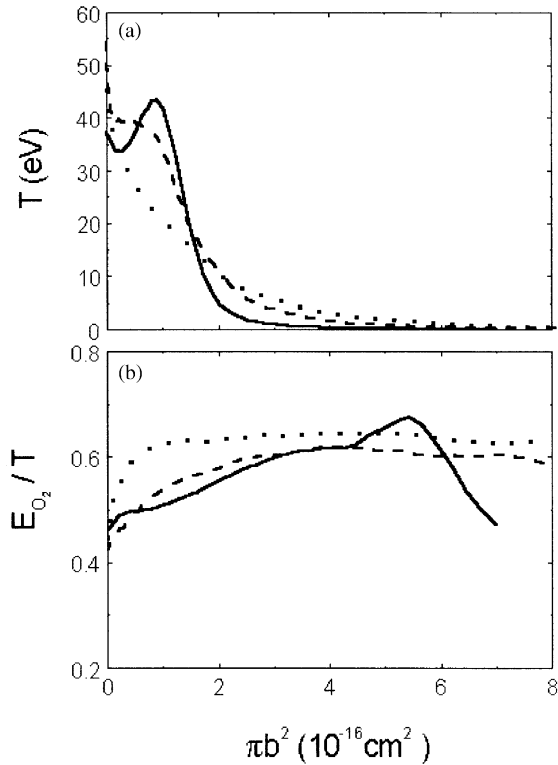


Fig. 4. (a) The average energy transfer, T , to the target molecule vs. impact parameter, b , for $\text{O} + \text{O}_2$ and (b) the fraction, E_{cm}/T , going into internal motion (vibration and rotation) of the struck molecule. Results are similar for $\text{N} + \text{N}_2$. 1 keV (solid line), 200 eV (dashed), 60 eV (dotted).

$\text{N}_2 + \text{N}_2$ and $\text{O}_2 + \text{O}_2$ are given at the energies relevant for escape by energetic recoils from a molecular atmosphere. Such cross sections have not been available to date and have typically been assumed to be hard sphere cross sections having a constant size. This is seen to be incorrect. Finally, for the escape of molecules from an atmosphere dominated by atoms at the exobase, the cross sections for atom–molecule collisions should be used, corrected by the appropriate center of mass energy.

When modeling the effect of energetic ions or atoms incident on an atmosphere, either the energy transfer to the target molecule vs. impact parameter or angular differential cross sections are needed. Unfortunately, these forms are not independent of energy, but the results averaged over molecular orientation do depend on energy in a simple way, as shown in Fig. 4. In Fig. 4(a), the average energy transfer to the target molecule vs. impact parameter for $\text{O} + \text{O}_2$ is displayed. At a low energy, it has a dependence on b like that seen in atom–atom collisions, but at 1 keV when binary encounters dominate, a peak at the average apparent separation of the atoms in the molecule is seen. In Fig. 4(b), the average fraction of the energy transfer to the target molecule going into internal degrees of freedom is shown. This is only slowly varying with b to some value of b where it decays rapidly. These ratios are very similar for $\text{N} + \text{N}_2$ collisions at the same collision velocity. Finally, in Fig. 5 the probability of

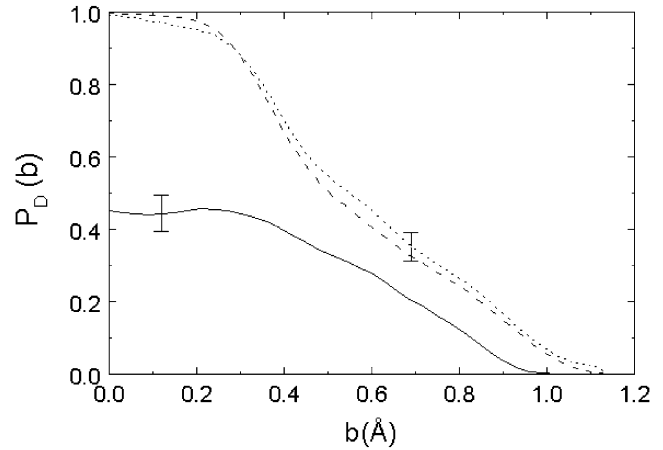


Fig. 5. The probability of a dissociation vs. impact parameter, b , for 1 keV (solid line) 200 eV (dashed), and 60 eV (dotted) O on O_2 . Similar results are obtained for $\text{N} + \text{N}_2$ if one scales b via the dissociation cross section in Fig. 2.

dissociation vs. impact parameter is given, a quantity also useful in modeling atmospheric sputtering. Over the energy region for which the cross section in Fig. 2 is flat or slowly varying with incident energy, the probability of dissociation vs. b also changes significantly. At higher energies, collisional dissociation decreases and electronically-induced dissociation eventually dominates.

4. Summary

We have calculated collisional dissociation cross sections for energetic O atoms incident on a number of molecules that occur at the exobases of planetary and satellite atmospheres. In these calculations we use the ρ – τ data (deflection of energetic incident O) to extract interaction potentials in the form of pair potentials. These potentials are then used to calculate the collisional dissociation cross sections. The extracted potentials differ significantly from the model potentials (Abrahamson 1969; Macheret and Adamovich, 2000), from potentials extracted from low energy collision data, from the so-called ‘universal’ (ZBL) pair potentials and from the ‘individual’ potentials. When applying pair potentials, the useful binary encounter approximation (Sieveka and Johnson, 1984; Johnson, 1990) is found to be valid well above the effective threshold but overestimates the dissociation at low collision energies. This simple method can give useful results if an artificial dissociation energy is used as a fitting parameter. This energy differs from the molecular dissociation energy because it accounts for the energy transfer to the center of mass of the molecule at large separations in slow collisions. We also found that the ZBL potentials, which we had been using in the earlier work, may be valid for atom–atom collisions but considerably overestimated the energy transfer cross sections if used in atom–molecule collisions. Finally, at higher energies than those shown here, electronically-induced dissociation must be included. Such calculations are in progress.

Due to the interest in Titan which has N_2 at the exobase, we used a rough model for obtaining the effective $N + N$ pair potential from the $O + O$ and $O + N$ pair potentials. These are then used to calculate the $N + N_2$ cross sections given here. Cross sections for this system based on first principle are also in progress. Useful fits to the dissociation cross sections are given in Table 2. Also given are the cross section controlling energy deposition in an atmosphere (S_n) and escape from the atmosphere (σ_d). These should be used to compliment our recent accurate calculation of the escape cross section for ground state collisions of $O + O$ (Tully and Johnson, 2001).

The results obtained here have recently been used in describing the collisional sputtering of the atmospheres of Titan (Schematovich et al., 2001) and Europa (Schematovich and Johnson, 2001). At Europa, it was shown that Saur et al. (1998) overestimated the energy transfer to atmospheric O_2 . Further, at Mars we used such calculations to correct a model (Kass and Yung, 1995) which suggested that the CO_2 molecules at the exobase significantly enhanced atmospheric sputtering yields (Leblanc and Johnson, 2001). The data presented here is now available for additional detailed modeling of atmospheric sputtering.

Acknowledgements

This work was supported by the NASA's Planetary Atmospheres Program.

References

- Abrahamson, A.A., 1969. Born–Mayer-type interatomic potential for neutral ground-state atoms with $Z=2$ to $Z=105$. *Phys. Rev.* 178, 76–79.
- Bougher, S.W., Engel, S., Roble, R.G., Foster, B., 1999. Comparative terrestrial planet thermospheres 2. Solar cycle variation of global structure and winds at equinox. *J. Geophys. Res.* 104, 16 591–16 611.
- Carlson, R.W., 1999. A tenuous carbon dioxide atmosphere on Jupiter's moon Callisto. *Science* 283, 820–821.
- Cruikshank, D.P., Roush, T.L., Opwen, T.C., Geballe, T.R., deBergh, C., Schmitt, B., Brown, R.H., Bartholomew, M.J., 1993. Ices on the surface of Triton. *Science* 261, 742–745.
- Foreman, P.B., Lees, A.B., Pol, P.K., 1976. Repulsive potentials for the interaction of oxygen atoms with the noble gases and atmospheric molecules. *Chem. Phys.* 12, 213–224.
- Fuls, E.W., Jones, P.R., Ziemba, F.P., Everhardt, E., 1957. Measurement of large-angle single collisions between helium, neon and argon atoms at energies to 100keV. *Phys. Rev.* 107, 704.
- Gartner, K., Hehl, K., 1979. Description of elastic atom–atom scattering. *Phys. Status Solidi B* 94, 231–238.
- Hall, D.T., Strobel, D.F., Feldman, P.D., McGrath, M.A., Weaver, H.A., 1995. Detection of an oxygen atmosphere on Jupiter's moon Europa. *Nature* 373, 677–681.
- Hall, D.T., Feldman, P.D., McGrath, M.A., Strobel, D.F., 1998. The far-ultraviolet oxygen airglow of Europa and Ganymede. *Astrophys. J.* 499, 475.
- Johnson, R.E., 1982. Introduction to atomic and molecular collisions. Plenum, New York, 1982, p. 52.
- Johnson, R.E., 1990. Energetic Charged-Particle Interactions with Atmospheres and Surfaces. Springer, Berlin.
- Johnson, R.E., 1994. Plasma-ion sputtering of an atmosphere. *Space Sci. Rev.* 69, 215.
- Johnson, R.E., Luhmann, J.G., 1998. Sputter contribution to the atmospheric corona on Mars. *J. Geophys. Res.* 103, 3649.
- Johnson, R.E., Schnellenberger, D., Wong, D.C., 2000. The sputtering of an oxygen thermosphere by energetic O^+ . *J. Geophys. Res.* 105, 1659–1670.
- Kass, D.M., Yung, Y.L., 1995. Loss of atmosphere from Mars due to solar-wind induced sputtering. *Science* 268, 697.
- Leblanc, F., Johnson, R.E., 2001. Sputtering of an atmosphere with molecules at the exobase. *Planetary and Space Science* 49 (6), 645.
- Lindsay, B.G., Merrill, R.L., Straub, H.C., Smith, K.A., Stebbings, R.F., 1998. Absolute differential and integral cross section for charge transfer of keV O^+ with N_2 . *Phys. Rev.* 57, 331–337.
- Macheret, S.O., Adamovich, I.V., 2000. Semiclassical modeling of state-specific dissociation rates in diatomic gases. *J. Chem. Phys.* 113, 7351–7361.
- Pospieszalska, M.K., Johnson, R.E., 1996. Monte Carlo calculations of the plasma ion-induced sputtering of an atmosphere: SO_2 ejected from Io. *J. Geophys. Res.* 101, 7565–7573.
- Saur, J., Strobel, D.F., Neubauer, F.M., 1998. Interaction of the Jovian magnetosphere with Europa: constraints on the neutral atmosphere. *J. Geophys. Res.* 103, 19947.
- Schafer, D.A., Newman, J.H., Smith, K.A., Stebbings, R.F., 1987. Differential cross sections for scattering of 0.5-, 1.5-, and 5.0-keV oxygen atoms by He, N_2 , and O_2 . *J. Geophys. Res.* 92, 6107–6113.
- Schematovich, V.I., Johnson, R.E., 2001. Near-surface oxygen atmosphere at Europa. *Adv. Space Res.*, in press.
- Schematovich, V.I., Tully, C., Johnson, R.E., 2001. Hot nitrogen corona at Titan. *Adv. Space Res.*, in press.
- Sieveka, E., Johnson, R.E., 1984. Ejection of atoms and molecules from Io by plasma ion impact. *Astrophys. J.* 287, 418–426.
- Smith, G.J., Gao, R.S., Lindsay, B.G., Smith, K.A., Stebbings, R.F., 1996. Absolute differential cross sections for the scattering of kilo-electron-volt O atoms. *Phys. Rev.* 53, 1581–1588.
- Tully, C., Johnson, R.E., 2001. Low energy collisions between ground state oxygen atoms. *Planet. Space Sci.* 49, 533–537.
- Wong, M., Johnson, R.E., 1996. A three-dimensional azimuthally symmetric model atmosphere for Io. 2. Plasma effect on the surface. *J. Geophys. Res.* 101, 23 255–23 259.
- Yelle, R.V., Strobel, D.F., Lellouch, E., Gautier, D. 1997. Engineering models for Titan's atmosphere. In: Wilson, A. (Ed.), Huygens Science Payload and Mission. ESA SP-1177, ESTEC, Noordwijk, Netherlands, pp. 243–256.
- Zeigler, J.F., Biersak, J.P., Littmark, V., 1985. The Stopping and Range of Ions in Solid. Pergamon, Tarrytown, NY.