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Sputter contribution to the atmospheric corona on Mars

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Abstract. Pickup-ion-induced sputtering, a potentially important nonthermal loss mechanism for the atmosphere of Mars, will also increase the content of the oxygen corona. This atmospheric sputtering process is shown to provide a small fraction of the corona in the present epoch but is equivalent to or dominates the dissociative recombination contribution for the earlier epochs modeled by *Zhang et al.* [1993]. The addition of sputtered atoms to the corona initiates feedback processes which can enhance the atmospheric sputtering rate in the present epoch but limits it in the earliest epoch considered. It is also shown that the sputter contribution to the corona has the same dependence on altitude as the dissociative recombination component and it may be a significant contribution during contemporary solar maximum conditions. The possible detection of the sputter-produced component of atomic O in the corona during solar maximum conditions may be the most promising way of confirming the significance of this nonthermal loss mechanism at Mars.

1. Introduction

Oxygen atoms in the Martian atmospheric corona are ionized by the solar EUV and the solar wind electrons. These ions are accelerated and either swept away by the solar wind fields, an atmospheric loss process, or they reimpact the atmosphere. Those ions impacting the atmosphere can lead to direct collisional loss [*Sieveka and Johnson*, 1984] or to loss of atoms and molecules from the atmosphere by the cascade of collisions initiated by the incident ion, a process that has become known as atmospheric sputtering [*Johnson*, 1990, 1994]. Although the magnitude of this process is still debated [*Krymskii and Breus*, 1996; *Lammer et al.*, 1996; *Johnson and Liu*, 1996; *Kass and Yung*, 1996; *Hutchins et al.*, 1997], it may have caused significant atmospheric loss [*Luhmann et al.*, 1992; *Jakosky et al.*, 1994; *Kass and Yung*, 1995] and may be responsible for measured isotope ratios for Ar and N [*Jakosky et al.*, 1994; *Pepin*, 1994; *Bogard*, 1997; *Jakosky and Jones*, 1997].

The pickup-ion-induced sputtering process not only results in atmospheric loss, it also populates the corona with energized atoms [*Sieveka and Johnson*, 1985; *McGrath and Johnson*, 1987; *Johnson*, 1990]. This will, in turn, allow enhanced pickup-ion formation, resulting in an interesting feedback process. This feedback process can be important in determining the sputtering rates [*Johnson*, 1994; *Johnson and Liu*, 1996], possibly enhancing sputtering in the present epoch but limiting the atmospheric sputtering rate in the model of the earliest epoch considered by *Zhang et al.* [1993]. Below, we use calculated values for the atmospheric sputtering rate to estimate the sputter contribution to the corona in these epochs and to examine whether the sputter corona can be detected by spacecraft in the present epoch.

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2. Sputtered Corona

In calculating the density of the corona, we consider a flux of oxygen pickup ions incident onto the Martian exobase [*Luhmann et al.*, 1992]. The energy spectra of the recoil particles which have been set in motion in the atmosphere by energetic ions have been determined both by Monte Carlo modeling [e.g., *Watson and Haff*, 1982; *Luhmann and Kozyra*, 1991; *Pospieszalska and Johnson*, 1996] and by solutions to the Boltzmann equation [*Johnson*, 1990, 1994]. It has the form

$$f(E) \approx \beta E_i/E^2 \qquad E_i > E \gg kT_x \tag{1}$$

where E_i is the incident particle energy, E the recoil particle energies, and T_x the temperature at the exobase. In (1), β is a parameter which depends on the incident ion angle and energy but is only weakly dependent on the collision cross section [*Johnson*, 1990; 1994]. Since the energy spectrum in (1) is always obtained when the interacting particle has an energy much greater than the background temperature, it also applies to energetic recoils produced by dissociative recombination, with E_i replaced by the energy release [*Johnson*, 1990, 1994]. Although the temperature and the altitude of the exobase can also be affected by the sputtering process [*Johnson*, 1990; *Pospieszalska and Johnson*, 1992, 1996; *Wong and Johnson*, 1995], here we use values determined by EUV heating [*Zhang et al.*, 1993].

A description of the energy spectrum of the atoms and molecules at the exobase requires a Monte Carlo particle tracking calculation [*Pospieszalska and Johnson*, 1992, 1996; *Kass and Yung*, 1995; M. Wong and R. E. Johnson, unpublished manuscript, 1997]. However, it can be roughly approximated by a Maxwell-Boltzmann distribution determined by T_x and an energetic tail, determined by (1), extending down in energy to $E \approx kT_x$. Using (1), an analytic expression for certain simple geometries has been derived for the sputter contribution to the atmospheric corona for a single-component atmosphere [*Watson et al.*, 1980; *Johnson*, 1990]. For a spherical object experiencing uniform ion bombardment, the expres-

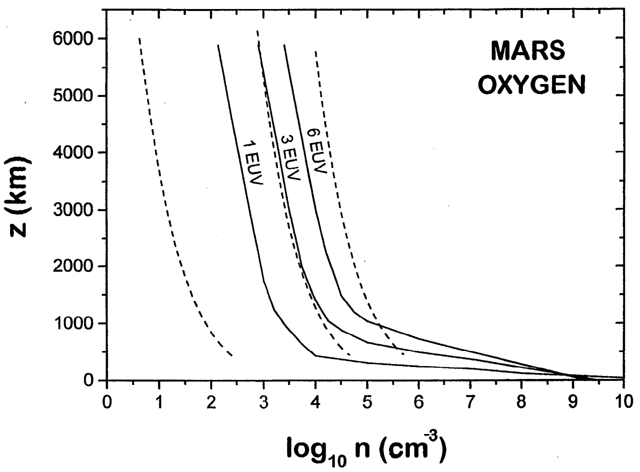

Figure 1. Oxygen densities *n* versus altitude *z* for the three solar intensities studied by *Luhmann et al.* [1992]: 1 EUV is solar minimum, 3 and 6 EUV are 3 and 6 times the 1 EUV value. Solid lines are the O densities produced by the dissociative recombination process calculated by *Zhang et al.* [1993]. Dashed lines are the sputter contribution to the corona calculated here using the L&J sputtering yields and ion fluxes in Table 1. This ignores the change in the exobase altitude and temperature due to ion bombardment and any enhancements due to feedback processes at low luminosity or any suppression of the yield due to feedback at the high luminosities.

sion is written in terms of $x = r_x/r$, where r_x is the exobase altitude and r the distance from the planet. The sputter-produced coronal density obtained using (1) is given in equations (4D.5) and (4D.6) of *Johnson* [1990]:

$$n_b^s(r) = n_0\Bigg[(1-x)^{-3/2}\tan^{-1}\left(\frac{x}{1-x}\right)^{1/2} + (2x-1)\,x^{1/2}/(1-x) - (1-x^2)^{1/2} \cdot [(1+x)^{3/2}\tan^{-1}x^{1/2} - (1-x)x^{1/2}/(1+x)^{1/2}]\Bigg] \tag{2a}$$

$$n_e^s(r) = \frac{\pi}{4}n_0[(1-x)^{-3/2} - (1-x^2)^{1/2}(1+x)^{3/2}] - \frac{n_b}{2} \tag{2b}$$

Here n_b^s is the bound component and n_e^s the escaping contribution to the corona with the total density $n^s = n_b^s + n_e^s$. In (2a) and (2b) the quantity n_0 is

$$n_0 = Y_x\left(\frac{\Phi_i}{v_{\rm es}}\right)\left(\frac{kT_x}{U_x}\right) \tag{3}$$

where Φ_i is the pickup-ion flux, $v_{\rm es}$ is the escape velocity, and U_x is the gravitational escape energy at the exobase of the planet. The yield Y_x is the number of recoils set in motion across the exobase by an incident ion, which depends on the energy deposition and on the momentum transfer cross section between O atoms. At larger r the expression in (2) reduces to $n^s(r) \rightarrow (\pi/2)\ n_0\ (r_x/r)^2$. (Care must be taken in a multicomponent atmosphere, as each escaping species can have a different collisional interaction cross section and hence a very different exobase altitude [*Johnson*, 1994].

An expression simpler than those in (2a) and (2b) is given for a "flat" atmosphere (gravity constant equation) in (4.19b) of *Johnson* [1990]. The equivalent of the atmospheric scale height is $\sim(H_c/4)$, in the notation of *Johnson* [1990], which equals $(r_x/4)$. That is, for atmospheric sputtering the density decays to $\sim$0.37 of its value at the exobase in a distance of about one-fourth of the planet's radius! Because the approximate energy spectrum in (1) is independent of mass, the "scale height" for the flat atmosphere (i.e., no escape) is also independent of the atomic mass. Therefore the extent of the sputtered atmosphere is much larger than that of the thermal atmosphere, determined by a scale height $(H_x) = [kT_x/U_x]r_x$. Defining $z = (r - r_x)$ near the exobase, both the flat atmosphere result and the expression in (2) above give

$$n^s(z) \approx (\pi/2)n_0(r_x/z)^{3/2} \tag{4}$$

Such a dependence is seen, over a limited range of z, for the sputter-produced corona of Io [*Schneider et al.*, 1989] and Na in the sputtered corona of Europa [*Brown and Hill*, 1996].

The parameters used to calculate the sputter-produced coronal population (dashed lines in Figure 1) are given in Table 1. The number of atoms or molecules which are set in motion near the exobase and which escape the gravitational field of the planet is called the yield Y. Values of Y are estimated by *Luhmann et al.* [1992] and *Jakosky et al.* [1994] (hereinafter, L&J) or *Kass and Yung* [1995, 1996] (hereinafter, KY). The L&J calculated yield has two components [*Johnson*, 1990, 1992], a cascade contribution having a recoil atom energy spectra like that in (1) and a single-collision component, since atoms in the corona can be directly ejected by the incident ion. The latter can be an efficient process because of the angular distribution of the struck particles [*Sieveka and Johnson*, 1984], but it does not add to the coronal density in the same way as the cascade of recoils. Whereas the size of this component is a nonnegligible fraction of the sputter-produced escape flux calculated by L&J, it is small compared with the collision-induced yield of atoms crossing the exobase, Y_x.

Since the cascade of recoils has the energy distribution in (1), the recoil contribution to Y can be multiplied by (U_x/kT_x) to give Y_x. Because the single-collision contribution to Y is much smaller than the recoil contribution and the range of yield values in Table 1 is large, we multiplied the total L&J yields by (U_x/kT_x) to estimate Y_x. Therefore in (3) the product $(Y_x\ kT_x/U_x)$ is equal to Y. This is used in (2a) and (2b) to calculate the pickup-ion-induced contribution to the coronal density shown in Figure 1.

As predicted [*Johnson*, 1990, 1994], the sputter-produced component of the corona in Figure 1 has a dependence on altitude which is almost identical to that produced by dissociative recombination, since (1) applies in both cases. Of course, sputtering produces much more energetic particles and will eventually dominate at higher altitudes. From Figure 1, it is seen that at a solar intensity corresponding to 1 EUV, the dissociative-recombination-produced corona dominates the sputter contribution even if one uses the most optimistic sputtering rates (KY). This calculation is roughly representative of contemporary Mars at the average solar EUV flux [e.g., *Bougher and Roble* 1991] (see also Table 1, footnote e). However, it is also seen in Figure 1 that at higher solar luminosity (e.g., earlier epochs) the sputter-produced corona is comparable to or larger than the corona produced by dissociative recombination.

Of interest is the effect of sputtering on Mars at solar maximum when the ionizing flux is $\sim$2 EUV. We make a rough estimate using *Zhang et al*'s., [1993] 1 and 3 EUV calculations, a point we discuss below. The fraction of the corona produced by sputtering in the 2 EUV epoch is roughly $\frac{1}{4}$ to $\frac{1}{2}$ of that produced by dissociative recombination, taking either a logarithmic or linear extrapolation between the ratios for the 3 and 1 EUV periods. If the larger yields in Table 1 are used, then the sputter contribution would also be larger. In addition, *Fox* [1993] suggests that the exobase is larger than that assumed by *Luhmann et al.* [1992]. This would enhance the O to CO_2 ratio, which would enhance the effect described here. Therefore the coronal density detected by spacecraft could be measurably larger than that predicted by dissociative recombination in the ionosphere. Being able to distinguish this difference by spacecraft measurement would provide an important test of the pickup-ion sputtering process.

To apply the "historical" 3 EUV case of *Zhang et al.* [1993] to a present "3 EUV" case, the location of the ionopause must be considered. In calculating ion pickup, it has been assumed that planetary ions that are produced above the ionopause are exposed to the solar wind fields and thus energized and removed or reenter the atmosphere as sputterers. The nonlinear increase in the pickup-ion flux with increasing EUV flux of *Zhang et al.* [1993] occurs because the population of coronal O is enhanced and the ionization rate is enhanced. *Zhang et al.* [1993] adopted an ionopause altitude of 300 km in this calculation. This altitude was consistent with both the assumed high early solar wind pressures and present-day observations that suggest the ionopause generally does not occur below this altitude even for higher EUV levels. If we consider the present average solar wind pressure at Mars (for nominal 400 km/s proton velocity and 2.5 cm^{-3} density), a value ~6.7×10^{-9} dyn cm^2, and use the ionosphere pressure profile that is obtained from the model of Zhang et al. (their Figures 4a and 4b) along with the assumption that ion temperature is roughly equal to electron temperature near the top of the ionosphere (suggested by Viking Lander observations), we find that a "pressure balance" ionopause occurs near 300 km. Thus the *Zhang et al.* [1993] 3 EUV can approximate present-day Mars during high solar activity. However, because of the importance of determining whether the Mars corona has a sputter-produced component, a full calculation at solar maximum conditions is needed.

3. Pickup-Ion Production and Feedback Processes

If the pickup-ion formation rate directly scales to the coronal population above the ionopause, the increased density due to sputtering will result in a corresponding increase in the pickup-ion production rate. This will produce a feedback process which can further increase the coronal population. A simple expression is available for calculating the enhancement in the effective sputtering yield under these conditions (appendix) [*Johnson*, 1990, 1994]. Since the sputter component of the corona is roughly proportional to Y, defining a pickup-ion formation factor γ, gives

$$Y_{\text{enhanced}} = Y/(1 - \gamma Y) \tag{5}$$

The factor γ is roughly (τ_r/τ_i) where τ_i^{-1} is the local ionization rate and τ_r the residence time of an atom in the ionization region [*Sieveka and Johnson*, 1985]. The latter is determined by the mean excursion time for the ballistic trajectories.

The above enhancement ignores any increase in exobase altitude or temperature due to sputtering. However, it also ignores the fact that the enhanced coronal density can increase the minimum altitude (the ionopause, here) above which pickup ions form. This effect can limit the atmospheric sputtering rate.

Table 1. Sputtering Parameters

	Epoch[a]		
	1 EUV	3 EUV	6 EUV
L&J Y[b]	2.0	4.4	4.8
Upper Y[c]	6.	6.	6.
KY Y[d]	21/3	20/3	19/3
Φ_i,[e] ions/cm^2/s	5×10^5	9×10^7	1×10^9
r_x, km	175	215	310
v_{es}, km/s	2.31	2.29	2.27
U_x, eV	1.97	1.95	1.91
c_O[f]	0.1	0.3	0.8
c_{CO_2}[f]	0.9	0.7	0.2
γ[g]	0.01	0.28	1.4
$(1 - \gamma Y)^{-1}$[h]	~1.01–1.08	$\sim 2 \rightarrow \infty$	∞

The values given are for atomic species, all presumed to be O, i.e., v_{es} and U are for O. Therefore, C from CO_2 and N from N_2 are treated as O in this paper.

[a] Epochs examined by *Zhang et al.* [1993] and *Luhmann et al.* [1992].

[b] Total atomic yield for a mixture of O and CO_2 as corrected by *Jakosky et al.* [1994, Table II], i.e., sputtered CO and CO_2 are ignored. This gives a rough lower bound to the total Y but includes the single-collision contribution discussed in text.

[c] Approximate maximum yield [*Jakosky et al.*, 1994, Table II] as if the species at the exobase were fully dissociated (C = O).

[d] KY yield; totally atomic in this model as molecules are assumed to always dissociate. Yields given in KY are divided by 3, as corrected by *Kass and Yung* [1996]. (Note that the yield in the 6 EUV period was given incorrectly by KY). These yields are close to the upper limits estimated by L&J.

[e] Pickup-ion flux as assumed by L&J (integrated over the results of *Zhang et al.* [1993]). Note that in calculating the pickup-ion flux in the present epoch, average solar conditions were used for the EUV flux which produced the O corona, but solar minimum conditions were used for the photoionization rate. Because electron impact ionization was the dominate source of O^+ (a point questioned by *Krymskii and Breus* [1996; *Luhmann*, 1996]), increasing the photoionization rate to average solar conditions would give ~20% enhancement in the pickup-ion flux. Although the field parameters [*Luhmann et al.*, 1993] exhibit smaller changes than the UV [*Torr and Torr*, 1985], this calculation should be redone for a number of solar conditions.

[f] These are the atomic concentrations at the exobase ignoring N_2 [*Zhang et al.*, 1993]. Note that CO_2 and O have very different exobase altitudes. In fact, since exobase altitude is defined by the mean free path for collisions, this altitude is different for O + O, O + CO_2, and CO_2 + CO_2 collisions. This effect is ignored here.

[g] Here γ is the factor to be multiplied by the escape yield Y to determine the formation of pickup ions which will reimpact the exobase. It is roughly equivalent to the escape flux divided by the incident ion flux in the work by *Zhang et al.* [1993]. See appendix for estimate of γY.

[h] Increase in the coronal density due to the simple pickup-ion feedback process discussed. Range of values are due to range of yields given in the table. Low values is obtained using the L&J yield ignoring the single-collision contribution; high value is obtained using the KY yields.

In the dominant region for forming ions which reimpact the exobase [*Zhang et al.*, 1993], the altitude dependence of the sputtering and dissociative recombination contributions to the corona are nearly identical. Therefore the quantity γY discussed above is roughly the ratio of the zero-order density of the sputter contribution to the dissociative recombination contribution: $\gamma Y \approx [(n^s)^0/n^{(0)}]$ (appendix). Using this in (5), the increase in the coronal density due to feedback is given in Table 1. That is, if the other effects mentioned are small, the results in Figure 1 can be multiplied by $(1 - \gamma Y)^{-1}$. In the present epoch (1 EUV) this enhancement is at most a few percent, whereas for 3 EUV intensity the enhancement is such that the sputter corona completely dominates that produced by dissociative recombination. This is also the case for the 6 EUV intensity (a very early epoch). Note however, for the 6 EUV case the exobase of *Zhang et al.* [1993] is slightly higher than the assumed ionopause, indicating the need for a self-consistent calculation of sputter loss.

For contemporary solar maximum conditions, we again use the rough averaging between the 1 and 3 EUV cases discussed above. The enhancement due to feedback increases the sputter contribution from $\sim\frac{1}{4}$–$\frac{1}{2}$ to $\sim\frac{1}{3}$–2 times that of dissociative recombination, depending on the extrapolation used. Therefore the net sputter contribution may be larger than the dissociative recombination contribution. For this reason, it is critical to calculate a model for the Martian corona at maximum solar intensity which includes feedback.

Because the increase in the coronal population changes the rate of formation of pickup ions, it will also change the direct loss of pickup ions. Therefore, ignoring feedback, the pickup-ion loss rate evaluated by L&J should be increased by $[(n^s)^0/n^0] \approx \gamma Y$ (appendix). Assuming that the feedback process described above does occur, this loss rate is further increased by $(1 - \gamma Y)^{-1}$. In the present epoch at average solar conditions (1 EUV) this enhancement is, again, not large, but it is likely to be significant at solar maximum. A detailed model is needed using appropriate thermosphere and ionosphere descriptions for solar maximum at Mars to compute the O corona from dissociative recombination. Having such a model would allow an observational assessment of the sputtering contribution. We suggest that the planet-B mission should provide the basic measurements to make this possible.

4. Conclusions

Using a simple model for the sputter contribution to the corona, we have shown in this paper that the recoil atoms set in motion by O^+ pickup-ion impact cause an increase the coronal density for contemporary average solar conditions (1 EUV) of only a few percent, making the detection of this component difficult. However, at solar maximum conditions (~2 EUV), we have made a rough estimate which indicates that the energetic O produced by pickup-ion sputtering can be a significant fraction of the oxygen corona. Our estimate is based on the results for the 1 and 3 EUV solar intensities in the model *Zhang et al.* [1993]. This analysis suggests that the effect on the corona of the pickup ion sputtering process could be determined by spacecraft measurements at solar maximum. Since we have also shown that the predicted scale heights of the dissociative recombination and sputtering components of the corona are the same, the direct detection of the sputter contribution to the corona or to the pickup-ion flux is difficult. Therefore contemporary ionospheric measurements, either in situ or radio osculations, will be required to analyze the consistency between the ionospheric and coronal density using dissociative recombination models. An excessive coronal density would imply that the efficiency of the proposed pickup-ion sputtering process at Mars is significant.

In the earlier epochs modeled by *Zhang et al.* [1993] the sputter-produced component is at least equivalent to the dissociative recombination component, ignoring the changes in the exobase altitude produced by adding sputtered O to the corona. The coronal enhancements described here will also affect the direct loss of pickup ions and will alter the exobase composition of the atmosphere, resulting in a higher concentration of atomic species at the exobase, reducing the estimated of the loss of CO_2. Clearly, self-consistent calculations of the ionopause and exobase altitude, which include the calculation of the sputter contribution to the corona, are needed. However, the estimates made here suggest that the sputter-produced component will dominate the corona in the earliest epoch studied (6 EUV) even if negative feedback occurs. This is also the case in the mid-epoch (3 EUV) if enhanced pickup ion impact is produced by the increased coronal density caused by atmospheric sputtering. Since Mars may have had a significant magnetic field in earlier epochs [e.g., *Hutchins et al.*, 1997], it is particularly important to know the size of the sputter-loss rate in the 3 EUV epoch of *Zhang et al.* [1993] (~2 Gyr). Since this epoch is near the time when the field is predicted to have decayed, sputter loss in this epoch will determine the role of atmospheric sputtering on the isotope ratios.

Appendix

A1. Enhancement in the Yield

The sputter enchancement in (5) is obtained by noting that pickup ions can be formed both from coronal O produced by dissociative recombination and by coronal O produced by sputtering. Calling $\Phi_i{}^{(0)}$ the pickup flux calculated by *Zhang et al.* [1993], the total sputter-produced flux Φ^s crossing the exobase is

$$\Phi^s = Y_x(\Phi_i^0 + \gamma_x \Phi^s) \tag{A1}$$

Here γ_x is the fraction of the sputter-produced O atoms that are ionized in the corona and reimpact the atmosphere, and Y_x is the number of atoms set in motion across the exobase by a pickup ion. Therefore the source strength at the exobase can be written $\Phi^s = (Y_x)_{\text{enhanced}}\,\Phi_i{}^{(0)}$. Using (A1), the enhanced yield is

$$(Y_x)_{\text{enhanced}} = Y_x/(1 - \gamma_x Y_x) \tag{A2}$$

Since the sputter-produced flux in (A1) is a source of coronal O, the net sputter contribution to the coronal density n^s can be calculated. If in the region of ionization (not too far from the exobase) the speed distributions of the sputtered and dissociative recombination coronas are similar, then $\Phi^s \approx \bar{v}_x\, n^s$, where $\bar{v}_x$ is the mean upward speed near the exobase. Therefore

$$n^s \approx [Y_x\gamma_x/(1 - \gamma_x Y_x)]n^{(0)} \tag{A3}$$

where $n^{(0)}$ is the initial density profile produced by dissociative recombination. This result assumes that the ionization rate is not changed by the increase in coronal O and ignores the change in exobase altitude. In (A3) the sputter contribution plotted in Figure 1, which ignores the feedback process, $(n^s)^0$, is equal to $Y_x\gamma_x n^{(0)}$, so that

$$(\gamma_x Y_x) \approx [(n^s)^0/n^{(0)}]$$

Finally, using the expression in (1) for the recoil energy spectrum and assuming the maximum recoil energy is much greater than U_x, then $Y_x \approx Y(U_x/kT_x)$, if Y is the recoil contribution to the sputter-escape yield. Therefore an effective ionization efficiency γ can be written using Y, $(\gamma Y) \approx (\gamma_x Y_x)$. Substituting γY into (A2) gives the results in (5) and the following paragraphs.

A2. Density Equations

In regard to (2a) and (2b), the symbol $\langle Y \rangle$ in (4D.5) and (4D.6) of *Johnson* [1990] means the angle-averaged yield for an isotropic flux of particles crossing the exobase of an atmosphere with $E > kT_x$. Note also that the book by *Johnson* [1990, p. 203] contains a typo, $U \rightarrow U^s$, satellite (planet) escape energy, and that $R \rightarrow R_s$ in the second line above (4D.5). The notation for the yield in certain places in *Johnson's* [1990] book is based upon using sputtering yields extracted from surface sputtering measurements. Therefore in the expression for a flat atmosphere [*Johnson*, 1990, equation (4.19b)], $\langle (2Y) \rangle$ is used instead of $\langle Y \rangle$ to emphasize that for an atmosphere (or a weakly bound solid) the binding criterion differs from that of a solid, giving a yield about twice as large.

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