Why an intrinsic magnetic field does not protect a planet against atmospheric escape*

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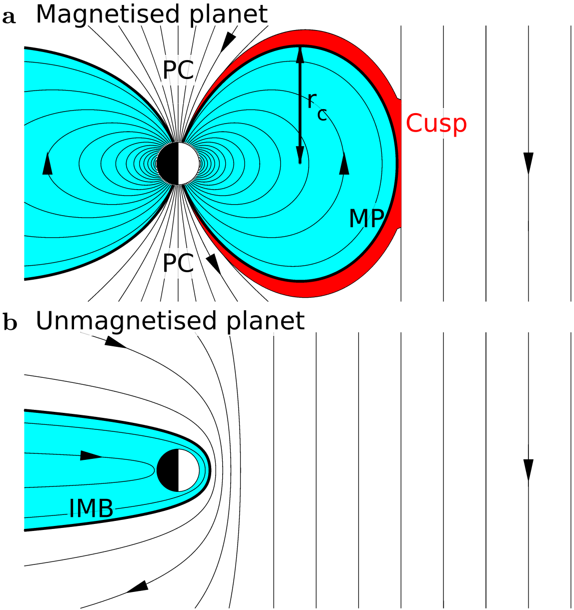
Introduction



Escape processes:

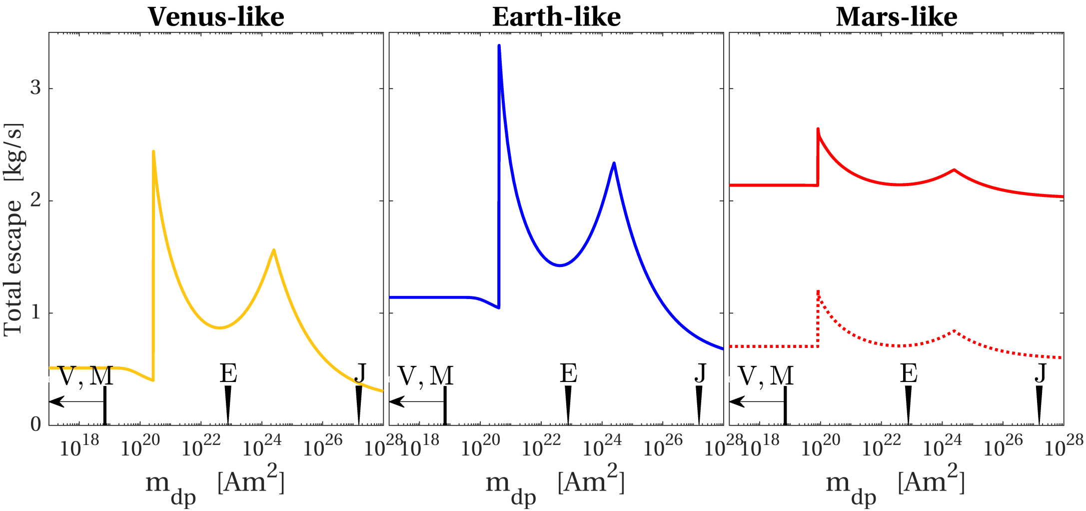
neutrals

- Jeans escape
- Dissociative recombination
- Sputtering

ions

- Ion pickup
- Cross-field ion loss
- Polar cap escape
- Cusp escape

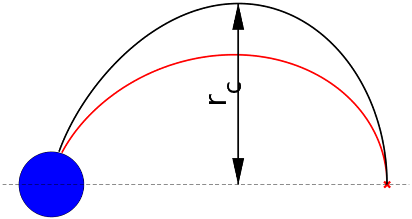
Results revealed



Magnetic model

The magnetopause standoff distance of a magnetized planet [1, 2]:

$$R_{\mathrm{MP}} = \left(\frac{\mu_0 f_0^2 m_{\mathrm{dp}}^2}{8\pi^2 n_{\mathrm{sw}} v_{\mathrm{sw}}^2} \right)^{1/6}, \qquad (1)$$



For r_{c} is found by field line tracing in the field[1]:

$$\mathbf{B}(x,z) = \mathbf{B}_{\mathrm{dp}}(x,z) + (2f_0 - 1)\mathbf{B}_{\mathrm{dp}}(R_{\mathrm{MP}}, 0) + \mathbf{B}_{\mathrm{sw}}, \qquad (2)$$

For Ω_{pc} a dipole field is used, yielding

$$\Omega_{\mathrm{pc}} = \begin{cases} 4\pi \left(1 - \sqrt{1 - \frac{r_{\mathrm{exo}}}{R_{\mathrm{MP}}}}\right) & \text{for } r_{\mathrm{IMB}} \leq R_{\mathrm{MP}} \\ 0 & \text{for } r_{\mathrm{IMB}} > R_{\mathrm{MP}} \end{cases} \qquad (3)$$

Jeans escape

Significant only for hydrogen

Escape rates on the order of $10^{25}\,\mathrm{s}^{-1}$ for Venus and $10^{26}\,\mathrm{s}^{-1}$ for Earth and Mars

The Jeans escape rate for species α is [3]

$$Q_{\mathrm{Je},\alpha} = 4\pi r_{\mathrm{exo}}^2 \sqrt{\frac{k_{\mathrm{B}} T_{\mathrm{exo}}}{2\pi m_\alpha}} n_{\mathrm{exo},\alpha} \left(1 + \frac{G M_{\mathrm{planet}} m_\alpha}{r_{\mathrm{exo}} k_{\mathrm{B}} T_{\mathrm{exo},\alpha}}\right) \exp\left(-\frac{G M_{\mathrm{planet}} m_\alpha}{r_{\mathrm{exo}} k_{\mathrm{B}} T_{\mathrm{exo}}}\right), \tag{4}$$

Dissociative recombination

O_2^+ ions recombine with electrons producing 7 eV atomic O.

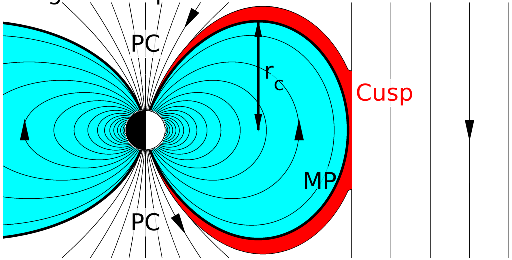
Can cause escape on Mars only.

Estimates vary a lot due to uncertain cross sections.

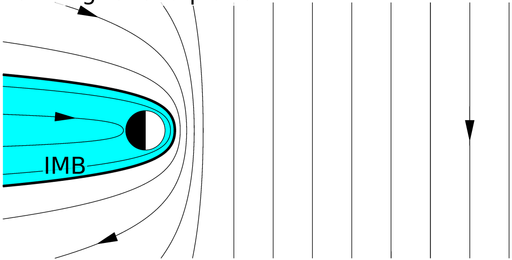
$5.9 \times 10^{25}\,\mathrm{s}^{-1}$ [4] and $5 \times 10^{24}\,\mathrm{s}^{-1}$ [5]

Cross-field ion loss

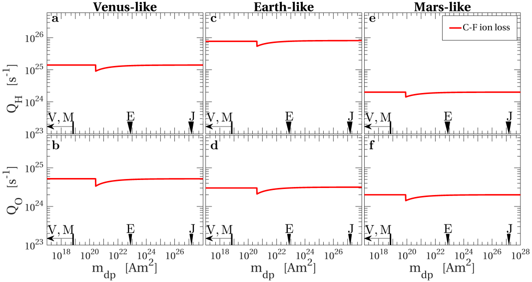
a Magnetised planet



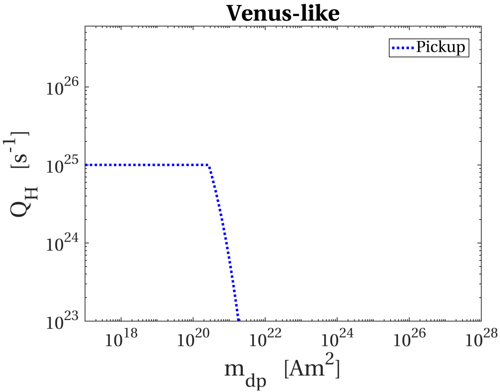
b Unmagnetised planet



$$Q_{\mathrm{cf},\alpha} = Q_{0,\mathrm{cf},\alpha} \frac{1 - \frac{\Omega_{\mathrm{pc}}}{4\pi}}{1 - \frac{\Omega_{\mathrm{pc,planet}}}{4\pi}}, \qquad (5)$$



Ion pickup



Ion pickup is proportional to the number of neutals outside the magnetopause or IMB.

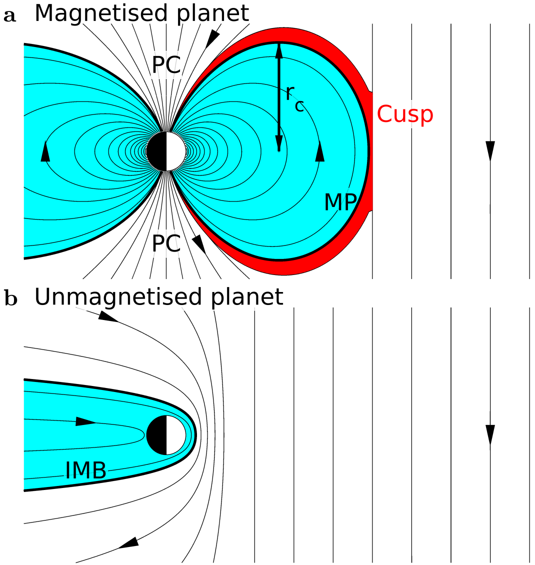
$$N_\alpha(\infty) - N_\alpha(r),$$

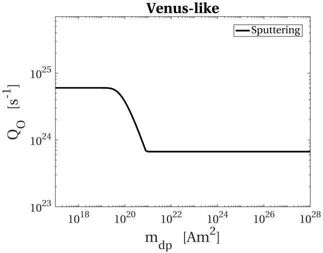
$$N_\alpha(r) = \int_0^r 4\pi r'^2 e^{-\frac{r'}{h_\alpha}} \mathrm{d}r' = 8\pi h_\alpha^3 - 4\pi\left(2h_\alpha^3 + 2h_\alpha^2 r + h_\alpha r^2\right) e^{-\frac{r}{h_\alpha}}, \tag{6}$$

where $h_\alpha = \frac{k_\mathrm{B} T_\mathrm{exo} r_\mathrm{exo}^2}{G M_\mathrm{planet} m_\alpha}$ is the scale height.

$$Q_{\mathrm{pu},\alpha} = Q_{0,\mathrm{pu},\alpha} \frac{N_\alpha(\infty) - N_\alpha(r_\mathrm{b})}{N_\alpha(\infty) - N_\alpha(r_\mathrm{exo})} = Q_{0,\mathrm{pu},\alpha} \frac{2h_\alpha^3 + 2h_\alpha^2 r_\mathrm{b} + h_\alpha r_\mathrm{b}^2}{2h_\alpha^3 + 2h_\alpha^2 r_\mathrm{exo} + h_\alpha r_\mathrm{exo}^2} e^{\frac{r_\mathrm{exo} - r_\mathrm{b}}{h_\alpha}} \tag{7}$$

Sputtering





Proportional to the number of neutrals within one gyroradius r_g above the exobase. We have

$$Q_{\mathrm{sp,O}} = Q_{0,\mathrm{sp,O}} \frac{\int\limits_{r_\mathrm{exo}}^{r_\mathrm{exo}+r_\mathrm{g}} r^2 e^{-\frac{r}{h_\mathrm{O}}}\,\mathrm{d}r}{\int\limits_{r_\mathrm{exo}}^{\infty} r^2 e^{-\frac{r}{h_\mathrm{O}}}\,\mathrm{d}r} =$$

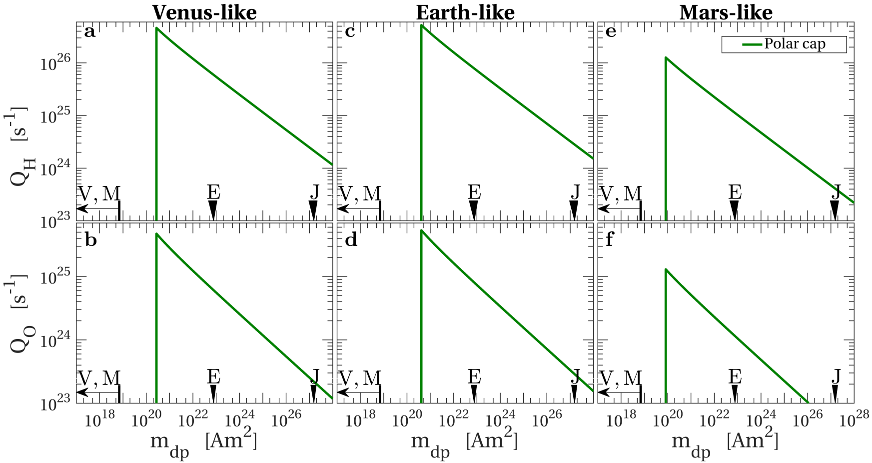
$$Q_{0,\mathrm{sp,O}} \left(1 - \frac{2h_\mathrm{O}^2 + 2h_\mathrm{O}\left(r_\mathrm{exo} + r_\mathrm{g}\right) + \left(r_\mathrm{exo} + r_\mathrm{g}\right)^2}{2h_\mathrm{O}^2 + 2h_\mathrm{O} r_\mathrm{exo} + r_\mathrm{exo}^2} e^{-\frac{r_\mathrm{g}}{h_\mathrm{O}}}\right). \tag{8}$$

We assume 1 keV O^+ ions to be typical [6]

Polar cap escape

Proportional to the polar cap area. We use the rate for Earth and scale according to

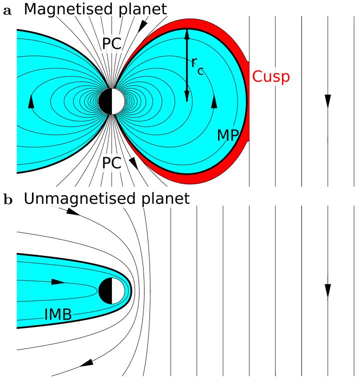
$$Q_{\mathrm{pc},\alpha} = Q_{0,\mathrm{pc},\alpha} \frac{\Omega_{\mathrm{pc}}}{\Omega_{\mathrm{pc,E}}} \left(\frac{r_{\mathrm{exo}}}{r_{\mathrm{exo,E}}} \right)^2 . \tag{9}$$

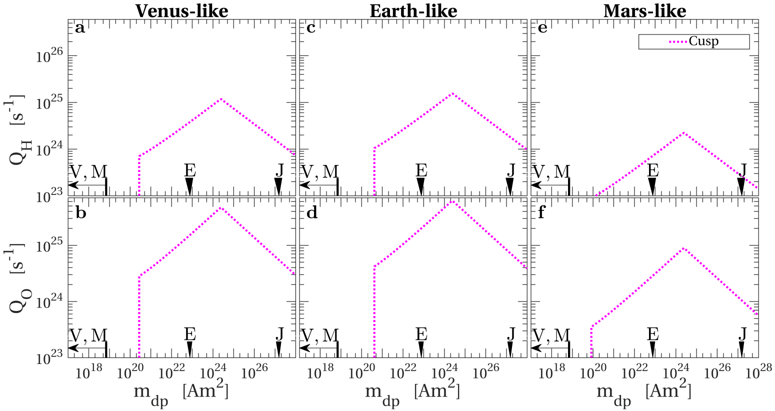


Cusp escape

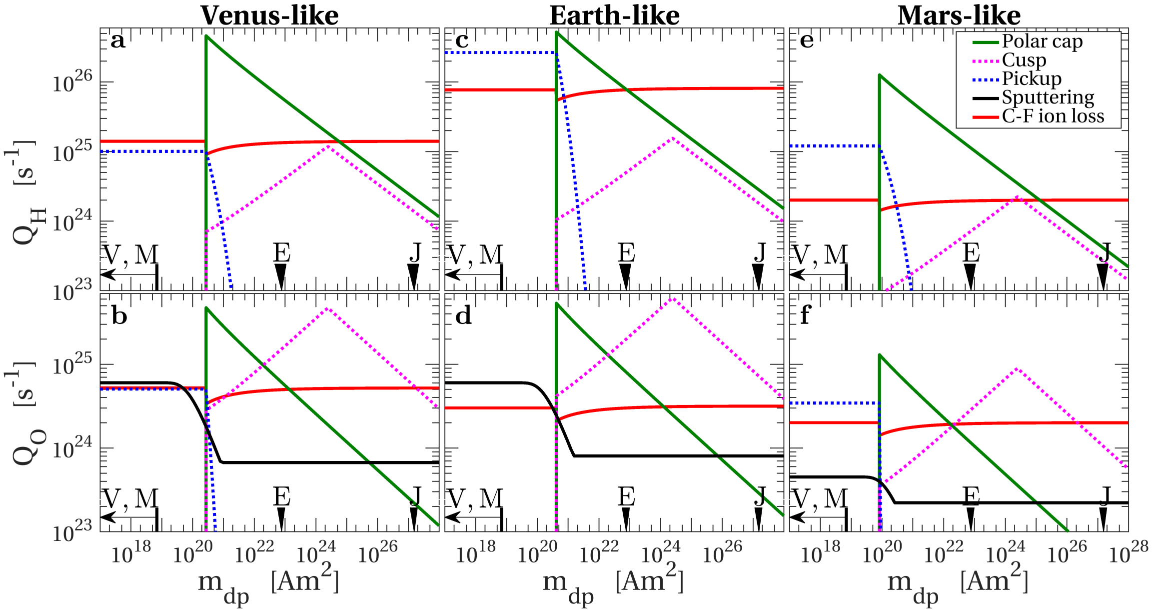
$$Q_{\mathrm{cu},\alpha} = \min\left(Q_{0,\mathrm{cu},\alpha} \left(\frac{r_\mathrm{c}}{r_\mathrm{c,E}} \right)^2, Q_{\max,0,\mathrm{cu},\alpha} \right) \cdot \frac{\Omega_\mathrm{pc}}{\Omega_\mathrm{pc,E}} \left(\frac{r_\mathrm{exo}}{r_\mathrm{exo,E}} \right)^2, \tag{10}$$

where $Q_{0,\mathrm{cu},\alpha}$ is the cusp escape rate for present-day Earth, $Q_{\max,0,\mathrm{cu,H}} = 5 \times 10^{25}\,\mathrm{s}^{-1}$ for hydrogen and $Q_{\max,0,\mathrm{cu,O}} = 2 \times 10^{26}\,\mathrm{s}^{-1}$ for oxygen are the limiting rates found by [7].

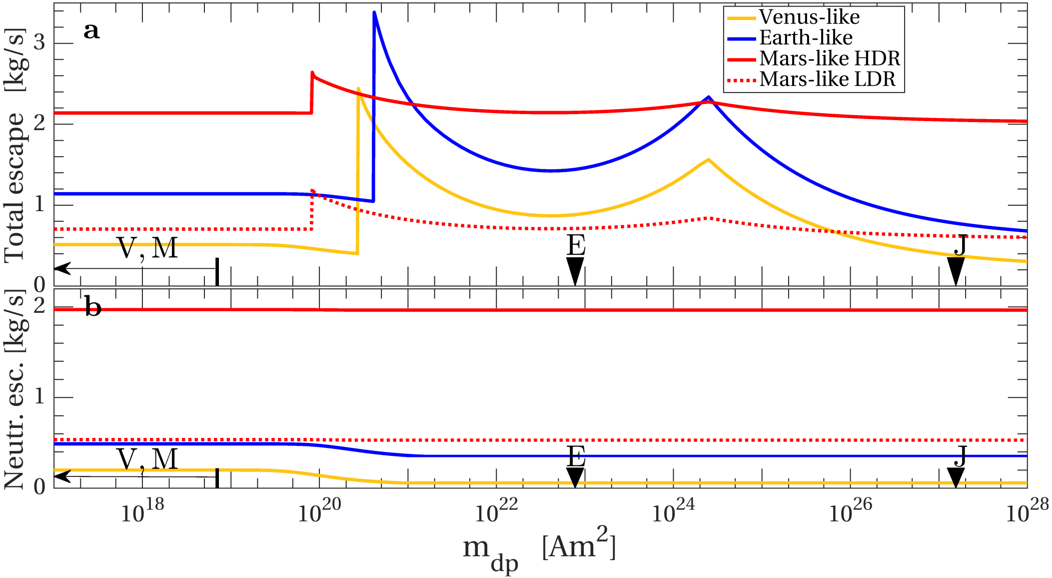




Processes

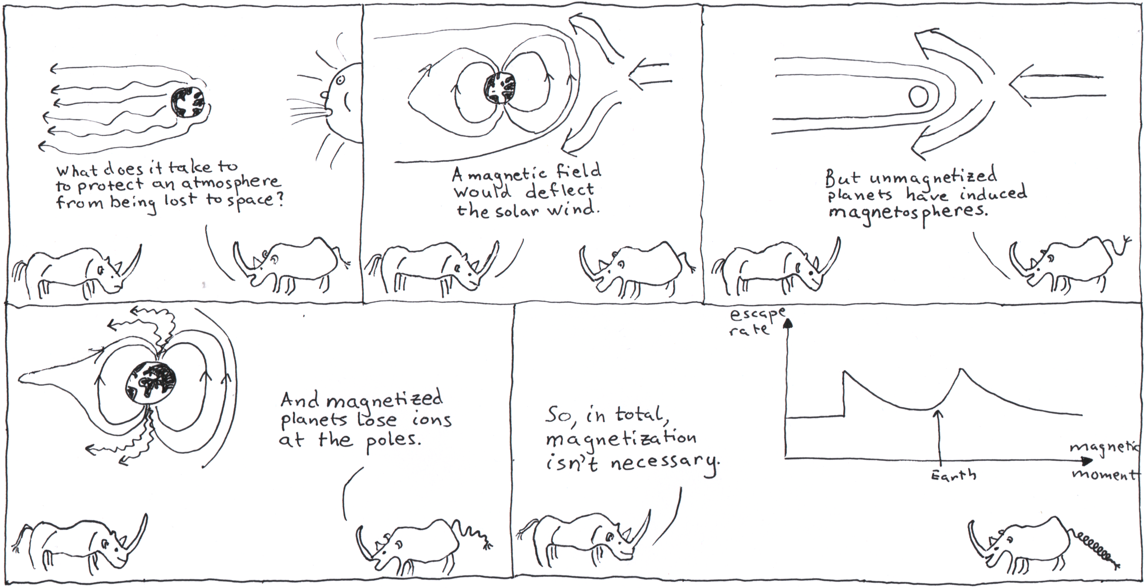

Venus-like
Earth-like
Mars-like
a
b
c
d
e
f
Polar cap
Cusp
Pickup
Sputtering
C-F ion loss
Q_H [s^{-1}]
Q_O [s^{-1}]
10^{23}
10^{24}
10^{25}
10^{26}
V, M
E
J
10^{18}
10^{20}
10^{22}
10^{24}
10^{26}
10^{28}
m_{dp} [Am^2]

Mass escape

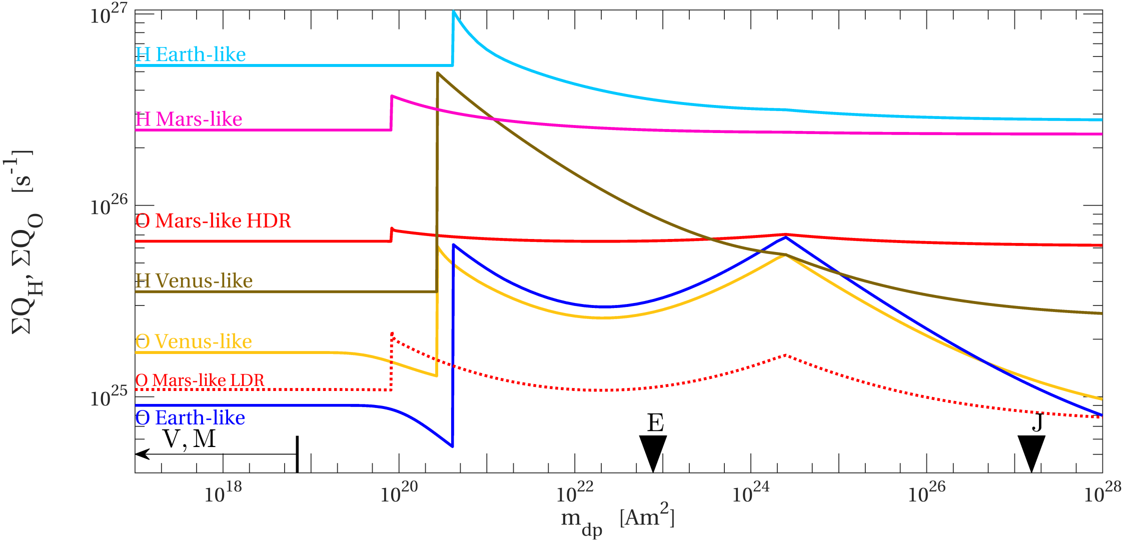


a
b
Venus-like
Earth-like
Mars-like HDR
Mars-like LDR
Total escape [kg/s]
Neutr. esc. [kg/s]
0
1
2
3
V, M
E
J
10^{18}
10^{20}
10^{22}
10^{24}
10^{26}
10^{28}
m_{dp} [Am^2]

Summary


What does it take to to protect an atmosphere from being lost to space?
A magnetic field would deflect the solar wind.
But unmagnetized planets have induced magnetospheres.
And magnetized planets lose ions at the poles.
So, in total, magnetization isn't necessary.
escape rate
Earth
magnetic moment

Hydrogen and oxygen



Planetary parameters

Parameter	Venus	Earth	Mars	Unit	Explanation
r_{planet}	6051.8	6371	3389.5	km	mean radius of planet
M_{planet}	4.867×10^{24}	5.972×10^{24}	6.417×10^{23}	kg	mass of planet
n_{sw}	1.2×10^{7}	6.0×10^{6}	2.6×10^{6}	m^{-3}	solar wind density
v_{sw}	4×10^{5}	4×10^{5}	4×10^{5}	ms^{-1}	solar wind speed
B_z	-12	-10	-7	nT	IMF B_z
r_{exo}	6271.8	6871	3609.5	km	radius of the exobase [8, 9]
r_{IMB}	6666.8	7647	4489.5	km	radius of the IMB [10, 11]
m_{d0}	$< 7 \times 10^{18}$	7.77×10^{22}	$< 2 \times 10^{18}$	Am^2	dipole moment [12, 13, 14]
$n_{\mathrm{exo,H}}$	1.3×10^{9}	8.5×10^{10}	2.5×10^{10}	m^{-3}	hydrogen density at exobase [15]
$n_{\mathrm{exo,O}}$	7.5×10^{10}	4×10^{10}	5.7×10^{12}	m^{-3}	oxygen density at exobase [16, 17, 18]
$T_{\mathrm{exo,H}}$	1020	900	350	K	exobase temperature [15, 8, 15]
$T_{\mathrm{exo,O}}$	6400	4100	300	K	exobase temperature [19, 17, 18]
$Q_{0,\mathrm{pc,H}}$	–	7.8×10^{25}	–	s^{-1}	ref. rate polar cap H escape [20]
$Q_{0,\mathrm{pc,O}}$	–	8×10^{24}	–	s^{-1}	ref. rate polar cap O escape [20, 21]
$Q_{0,\mathrm{cu,H}}$	–	5×10^{24}	–	s^{-1}	ref. rate cusp H escape [22]
$Q_{0,\mathrm{cu,O}}$	–	2×10^{25}	–	s^{-1}	ref. rate cusp O escape [23, 24, 22]
$Q_{0,\mathrm{pu,H}}$	1.3×10^{25}	5.3×10^{26}	2.3×10^{25}	s^{-1}	ref. rate pickup H escape [8]
$Q_{0,\mathrm{pu,O}}$	1.2×10^{25}	7.9×10^{22}	2.6×10^{32}	s^{-1}	ref. rate pickup O escape [25, 8, 26]
$Q_{0,\mathrm{cf,H}}$	1.4×10^{25}	7.7×10^{25}	2.0×10^{24}	s^{-1}	cross-field ion loss rate H [27, 28, 29]
$Q_{0,\mathrm{cf,O}}$	5.2×10^{24}	3×10^{24}	2.0×10^{24}	s^{-1}	cross-field ion loss rate O [30, 28, 29, 31]
$Q_{0,\mathrm{ldr,O}}$	0	0	5×10^{24}	s^{-1}	low diss. recomb. rate [5]
$Q_{0,\mathrm{hdr,O}}$	0	0	5.9×10^{25}	s^{-1}	high diss. recomb. rate [4]
$Q_{0,\mathrm{sp,O}}$	6×10^{24}	6×10^{24}	4.5×10^{23}	s^{-1}	ref. rate sputtering [6, 32, 33]

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