APPENDIX A: CHEMICAL NETWORK

In Tables A1–A14 we list the chemical reactions included in our model of primordial gas, along with the rate coefficients adopted and the references from which these rate coefficients were taken. Some of these reactions are discussed in more detail in Section 3.1. In these tables, $T$ is the gas temperature in K, $T_3 = T/300$ K, and $T_e$ is the gas temperature in units of eV.
Table A1. Chemical processes: collisional ionization (CI).

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>Rate coefficient (cm³ s⁻¹)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI1</td>
<td>H + e⁻ → H⁺ + e⁻ + e⁻</td>
<td>$k_{CI1} = \exp[-3.271396786 \times 10^1 + 1.3536556 \times 10^1 \ln T]$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$- 5.739522875 \times 10^0 (\ln T)^2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ 1.56315498 \times 10^6 (\ln T)^3$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$- 2.8770566 \times 10^{-1} (\ln T)$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ 3.48255977 \times 10^{-2} (\ln T)$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$- 2.63197617 \times 10^{-3} (\ln T)$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ 1.11945395 \times 10^{-4} (\ln T)$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$- 2.03914985 \times 10^{-6} (\ln T)$</td>
<td></td>
</tr>
<tr>
<td>CI2</td>
<td>D + e⁻ → D⁺ + e⁻ + e⁻</td>
<td>$k_{CI2} = k_{CI1}$</td>
<td>1</td>
</tr>
<tr>
<td>CI3</td>
<td>He + e⁻ → He⁺ + e⁻ + e⁻</td>
<td>$k_{CI3} = \exp[-4.409864886 \times 10^1 + 2.391596563 \times 10^1 \ln T]$</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$- 1.07532302 \times 10^1 (\ln T)^2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ 3.05803875 \times 10^6 (\ln T)^3$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$- 5.68511890 \times 10^{-1} (\ln T)^4$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ 6.79539123 \times 10^{-2} (\ln T)^5$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$- 5.00905610 \times 10^{-3} (\ln T)^6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ 2.06723616 \times 10^{-4} (\ln T)^7$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$- 3.64916141 \times 10^{-6} (\ln T)^8$</td>
<td></td>
</tr>
<tr>
<td>CI4</td>
<td>Li + e⁻ → Li⁺ + e⁻ + e⁻</td>
<td>$k_{CI4} = 3.11 \times 10^{-8} T_3^{0.163} \exp \left(\frac{-62700}{T}\right)$</td>
<td>2</td>
</tr>
</tbody>
</table>

Notes: T is the gas temperature in K, $T_3 = T/300$ K, and $T_e$ is the gas temperature in eV.


Table A2. Chemical processes: photorecombination (PR).

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>Rate coefficient (cm³ s⁻¹)</th>
<th>Notes</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR1</td>
<td>H⁺ + e⁻ → H + γ</td>
<td>$k_{PR1} = 2.753 \times 10^{-14} \left(\frac{3.85614}{T}\right)^{1.560} \left[1 + \left(\frac{11.518}{T}\right)^{0.407}\right]^{-2.242}$</td>
<td>Case A</td>
<td>1</td>
</tr>
<tr>
<td>PR2</td>
<td>D⁺ + e⁻ → D + γ</td>
<td>$k_{PR2} = k_{PR1}$</td>
<td>Case A</td>
<td>1</td>
</tr>
<tr>
<td>PR3</td>
<td>He⁺ + e⁻ → He + γ</td>
<td>$k_{PR3,ir,A} = 10^{-11} T^{-0.5} \left[12.72 - 1.615 \log T - 0.3162(\log T)^2 + 0.0493(\log T)^3\right]$</td>
<td>Case B</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$k_{PR3,ir,B} = 10^{-11} T^{-0.5} \left[11.19 - 1.676 \log T - 0.2852(\log T)^2 + 0.04433(\log T)^3\right]$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$k_{PR3,di} = T^{-1.5} \left[5.966 \times 10^{-4} \exp\left(\frac{-555200}{T}\right) + 1.613 \times 10^{-4} \exp\left(\frac{-555200}{T}\right) - 2.223 \times 10^{-5} \exp\left(\frac{-859800}{T}\right)\right]$</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>PR4</td>
<td>Li⁺ + e⁻ → Li + γ</td>
<td>$k_{PR4,ir} = 1.036 \times 10^{-11} \left(\frac{T}{1977}\right)^{0.5} \left[1 + \left(\frac{T}{1977}\right)^{0.5}\right]^{-0.612}$</td>
<td>Case B</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\times \left[1 + \left(\frac{T}{1977}\right)^{0.5}\right]^{-1.388}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$k_{PR4,di} = T^{-1.5} \left[2.941 \times 10^{-6} \exp\left(\frac{-634500}{T}\right) + 6.068 \times 10^{-7} \exp\left(\frac{-702400}{T}\right) - 7.753 \times 10^{-7} \exp\left(\frac{-827100}{T}\right)\right]$</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Notes: T is the gas temperature in K. Note that the recently revised values for PR1 and for the radiative recombination portions of PR3 and PR4 presented by Badnell (2006b) do not differ from the older rate coefficients quoted here by more than a couple of percent at the temperatures of interest in this study.

Table A3. Chemical processes: dissociative recombination (DR).

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>Rate coefficient (cm³ s⁻¹)</th>
<th>Notes</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR1</td>
<td>Htp + e⁻ → H + H</td>
<td>$k_{DR1} = 1.0 \times 10^{-8}$</td>
<td>$T \leq 617$ K  $T &gt; 617$ K</td>
<td>1</td>
</tr>
<tr>
<td>DR2</td>
<td>HD⁺ + e⁻ → H + D</td>
<td>$k_{DR2} = 7.2 \times 10^{-8}T^{-0.5}$</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>DR3</td>
<td>D⁺ + e⁻ → D + D</td>
<td>$k_{DR3} = 3.4 \times 10^{-9}T^{-0.4}$</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>DR4</td>
<td>H⁺ + e⁻ → Ht + H</td>
<td>$k_{DR4} = 2.34 \times 10^{-9}T^{-0.5}$</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>DR5</td>
<td>H⁺ + e⁻ → H + H + H</td>
<td>$k_{DR5} = 4.36 \times 10^{-9}T^{-0.5}$</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>DR6</td>
<td>H₂D⁺ + e⁻ → H + H + D</td>
<td>$k_{DR6} = 4.38 \times 10^{-9}T^{-0.5}$</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>DR7</td>
<td>H₂D⁺ + e⁻ → Ht + D</td>
<td>$k_{DR7} = 4.2 \times 10^{-9}T^{-0.5}$</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>DR8</td>
<td>H₂D⁺ + e⁻ → H + HD</td>
<td>$k_{DR8} = 1.2 \times 10^{-8}T^{-0.5}$</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>DR9</td>
<td>HD₂⁺ + e⁻ → D + D + H</td>
<td>$k_{DR9} = 4.38 \times 10^{-9}T^{-0.5}$</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>DR10</td>
<td>HD₂⁺ + e⁻ → D₂ + H</td>
<td>$k_{DR10} = 4.2 \times 10^{-9}T^{-0.5}$</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>DR11</td>
<td>HD₂⁺ + e⁻ → HD + D</td>
<td>$k_{DR11} = 1.2 \times 10^{-9}T^{-0.5}$</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>DR12</td>
<td>D⁺ + e⁻ → D₂ + D</td>
<td>$k_{DR12} = 5.4 \times 10^{-9}T^{-0.5}$</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>DR13</td>
<td>D₂⁺ + e⁻ → D + D + D</td>
<td>$k_{DR13} = 2.16 \times 10^{-8}T^{-0.5}$</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>DR14</td>
<td>HeH⁺ + e⁻ → He + H</td>
<td>$k_{DR14} = 3.0 \times 10^{-9}T^{-0.47}$</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>DR15</td>
<td>HeD⁺ + e⁻ → He + D</td>
<td>$k_{DR15} = 3.0 \times 10^{-9}T^{-0.47}$</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>DR16</td>
<td>He₂⁺ + e⁻ → He + He</td>
<td>$k_{DR16} = 6.1 \times 10^{-11}T^{-0.9}$</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>DR17</td>
<td>LiH⁺ + e⁻ → Li + H</td>
<td>$k_{DR17} = 3.8 \times 10^{-7}T^{-0.47}$</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>DR18</td>
<td>LiD⁺ + e⁻ → Li + D</td>
<td>$k_{DR18} = 3.8 \times 10^{-7}T^{-0.47}$</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>DR19</td>
<td>LiH₂⁺ + e⁻ → Li + Ht</td>
<td>$k_{DR19} = 1.6 \times 10^{-7}T^{-0.5}$</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>DR20</td>
<td>LiH₂⁺ + e⁻ → LiH + H</td>
<td>$k_{DR20} = 2.0 \times 10^{-8}T^{-0.5}$</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>DR21</td>
<td>LiH₂⁺ + e⁻ → Li + H + H</td>
<td>$k_{DR21} = 2.0 \times 10^{-8}T^{-0.5}$</td>
<td></td>
<td>13</td>
</tr>
</tbody>
</table>

Notes: $T$ is the gas temperature in K, and $T_3 = T/300$ K.

References: 1 – Schneider et al. (1994); 2 – Stromholm et al. (1995); 3 – Walmsley et al. (2004); 4 – McCall et al. (2004); 5 – Larsson et al. (1996); 6 – Roberts et al. (2004), based on Larsson et al. (1996); 7 – Larsson et al. (1997); 8 – Guberman (1994); 9 – Stancil et al. (1998), based on Guberman (1994); 10 – Carata et al. (1999); 11 – Krohn et al. (2001); 12 – same as corresponding H reaction; 13 – Thomas et al. (2006), C. Greene (private communication).
Table A4. Chemical processes: charge transfer (CT).

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>Rate coefficient (cm$^3$ s$^{-1}$)</th>
<th>Notes</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT1</td>
<td>H + D$^+$ → D + H$^+$</td>
<td>$k_{CT1} = 2.06 \times 10^{-10}T^{0.396}\exp\left(-\frac{31}{T}\right)$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ 2.03 \times 10^{-3}T^{-0.382}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT2</td>
<td>H + D$^-$ → D + H$^-$</td>
<td>$k_{CT2} = 6.4 \times 10^{-9}T^{0.41}$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>CT3</td>
<td>H + Htp → Ht + H$^+$</td>
<td>$k_{CT3} = 6.4 \times 10^{-10}$</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>CT4</td>
<td>H + HD$^+$ → HD + H$^+$</td>
<td>$k_{CT4} = 6.4 \times 10^{-10}$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CT5</td>
<td>H + D$_2^+$ → D$_2$ + H$^+$</td>
<td>$k_{CT5} = 6.4 \times 10^{-10}$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CT6</td>
<td>H + Hep → He + H$^+$ + γ</td>
<td>$k_{CT6} = 1.25 \times 10^{-15}T^{0.25}$</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>CT7</td>
<td>H + He$_2^+$ → He + He + H$^+$</td>
<td>$k_{CT7} = 1.0 \times 10^{-9}$</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>CT8</td>
<td>H + LiH$^+$ → LiH + H$^+$</td>
<td>$k_{CT8} = 1.0 \times 10^{-11} \exp\left(-\frac{67900}{T}\right)$</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>CT9</td>
<td>H + LiD$^+$ → LiD + H$^+$</td>
<td>$k_{CT9} = 1.0 \times 10^{-11} \exp\left(-\frac{67900}{T}\right)$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CT10</td>
<td>D + H$^+$ → H + D$^+$</td>
<td>$k_{CT10} = 2.0 \times 10^{-10}T^{0.402}\exp\left(-\frac{37.4}{T}\right)$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$- 3.31 \times 10^{-17}T^{1.48}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT11</td>
<td>D + H$^-$ → H + D$^-$</td>
<td>$k_{CT11} = 6.4 \times 10^{-9}T^{0.41}$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>CT12</td>
<td>D + Htp → Ht + D$^+$</td>
<td>$k_{CT12} = 6.4 \times 10^{-10}$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CT13</td>
<td>D + HD$^+$ → HD + D$^+$</td>
<td>$k_{CT13} = 6.4 \times 10^{-10}$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CT14</td>
<td>D + D$_2^+$ → D$_2$ + D$^+$</td>
<td>$k_{CT14} = 6.4 \times 10^{-10}$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CT15</td>
<td>D + Hep → He + D$^+$ + γ</td>
<td>$k_{CT15} = 1.1 \times 10^{-15}T^{0.25}$</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>CT16</td>
<td>D + He$_2^+$ → He + He + D$^+$</td>
<td>$k_{CT16} = 7.5 \times 10^{-10}$</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>CT17</td>
<td>D + LiH$^+$ → LiH + D$^+$</td>
<td>$k_{CT17} = 1.0 \times 10^{-11} \exp\left(-\frac{67900}{T}\right)$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CT18</td>
<td>D + LiD$^+$ → LiD + D$^+$</td>
<td>$k_{CT18} = 1.0 \times 10^{-11} \exp\left(-\frac{67900}{T}\right)$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CT19</td>
<td>Ht + H$^+$ → H + Htp</td>
<td>$k_{CT19} = [-3.3232183 \times 10^{-7}$</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ 3.3735382 \times 10^{-7} \ln T$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$- 1.4491368 \times 10^{-7} \ln T^2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ 3.4172805 \times 10^{-8} \ln T^3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$- 4.7813720 \times 10^{-9} \ln T^4$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ 3.9731542 \times 10^{-10} \ln T^5$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$- 1.8171411 \times 10^{-11} \ln T^6$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ 3.5311532 \times 10^{-13} \ln T^7$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\times \exp\left(-\frac{21337.15}{T}\right)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\times \exp\left(-\frac{21337.15}{T}\right)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT20</td>
<td>Ht + D$^+$ → D + Htp</td>
<td>$k_{CT20} = k_{CT19}$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CT21</td>
<td>Ht + Hep → He + Htp</td>
<td>$k_{CT21} = 7.2 \times 10^{-15}$</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>CT22</td>
<td>Ht + Hep → He + H + H$^+$</td>
<td>$k_{CT22} = 3.7 \times 10^{-14} \exp\left(-\frac{34}{T}\right)$</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>CT23</td>
<td>Ht + Li$^+$ → Li + Htp</td>
<td>$k_{CT23} = 3.0 \times 10^{-10}T^{-1.5}\exp\left(-\frac{116000}{T}\right)$</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>CT24</td>
<td>HD + H$^+$ → H + HD$^+$</td>
<td>$k_{CT24} = k_{CT19}$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CT25</td>
<td>HD + D$^+$ → D + HD$^+$</td>
<td>$k_{CT25} = k_{CT19}$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CT26</td>
<td>HD + Hep → He + HD$^+$</td>
<td>$k_{CT26} = 7.2 \times 10^{-15}$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CT27</td>
<td>HD + Hep → He + H$^+$ + D</td>
<td>$k_{CT27} = 1.85 \times 10^{-14} \exp\left(-\frac{34}{T}\right)$</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>CT28</td>
<td>HD + Hep → He + H + D$^+$</td>
<td>$k_{CT28} = 1.85 \times 10^{-14} \exp\left(-\frac{34}{T}\right)$</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>CT29</td>
<td>HD + Li$^+$ → Li + HD$^+$</td>
<td>$k_{CT29} = k_{CT23}$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CT30</td>
<td>D$_2$ + H$^+$ → H + D$_2^+$</td>
<td>$k_{CT30} = k_{CT19}$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CT31</td>
<td>D$_2$ + D$^+$ → D + D$_2^+$</td>
<td>$k_{CT31} = k_{CT19}$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CT32</td>
<td>D$_2$ + Hep → He + D$_2^+$</td>
<td>$k_{CT32} = 2.5 \times 10^{-14}$</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>CT33</td>
<td>D$_2$ + Hep → He + D$^+$ + D</td>
<td>$k_{CT33} = 1.1 \times 10^{-13}T^{-0.24}$</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>CT34</td>
<td>D$_2$ + Li$^+$ → Li + D$_2^+$</td>
<td>$k_{CT34} = k_{CT23}$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>CT35</td>
<td>He + H$^+$ → H + Hep</td>
<td>$k_{CT35} = 1.26 \times 10^{-9}T^{-0.75}\exp\left(-\frac{127500}{T}\right)$</td>
<td>15</td>
<td>$T \leq 10000$ K</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$T &gt; 10000$ K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT36</td>
<td>He + D$^+$ → D + Hep</td>
<td>$k_{CT36} = k_{CT35}$</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>
Table A4 – continued

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>Rate coefficient (cm$^3$ s$^{-1}$)</th>
<th>Notes</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT37</td>
<td>Li + H$^+$ → H + Li$^+$</td>
<td>$k_{CT37} = 2.5 \times 10^{-407^7.7^9 \exp \left( \frac{T}{1210} \right)}$</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>CT38</td>
<td>Li + H$^+$ → H + Li$^+$ + γ</td>
<td>$k_{CT38} = 1.7 \times 10^{-13T^{0.051} \exp \left( \frac{-T}{2920} \right)}$</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>CT39</td>
<td>Li + D$^+$ → D + Li$^+$</td>
<td>$k_{CT39} = 8.0 \times 10^{-22 T^{6.8 \exp \left( \frac{-T}{100} \right)}}$</td>
<td></td>
<td>18</td>
</tr>
<tr>
<td>CT40</td>
<td>Li + D$^+$ → D + Li$^+$ + γ</td>
<td>$k_{CT40} = 1.1 \times 10^{-13 T^{0.051} \exp \left( \frac{-T}{2920} \right)}$</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>CT41</td>
<td>Li + Htp → Ht + Li$^+$</td>
<td>$k_{CT41} = 3.0 \times 10^{-10 T^{1.5}}$</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>CT42</td>
<td>Li + HD$^+$ → HD + Li$^+$</td>
<td>$k_{CT42} = k_{CT41}$</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>CT43</td>
<td>Li + D$_2$ → D$_2$ + Li$^+$</td>
<td>$k_{CT43} = k_{CT41}$</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>CT44</td>
<td>LiH + H$^+$ → H + LiH$^+$</td>
<td>$k_{CT44} = 2.0 \times 10^{-15}$</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>CT45</td>
<td>LiH + D$^+$ → D + LiH$^+$</td>
<td>$k_{CT45} = 2.0 \times 10^{-15}$</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>CT46</td>
<td>LiD + H$^+$ → H + LiD$^+$</td>
<td>$k_{CT46} = 2.0 \times 10^{-15}$</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>CT47</td>
<td>LiD + D$^+$ → D + LiD$^+$</td>
<td>$k_{CT47} = 2.0 \times 10^{-15}$</td>
<td></td>
<td>21</td>
</tr>
</tbody>
</table>

**Notes:** T is the gas temperature in K, and $T_3 = T/300$ K.

**References:** 1 – Savin (2002); 2 – Dalgarno & McDowell (1956), scaled by D reduced mass; 3 – Karpas, Anicich & Huntress (1979); 4 – same as corresponding H reaction; 5 – Zygelman et al. (1989); 6 – Estimate by Stancil et al. (1998), based on Stancil et al. (1993); 7 – Stancil et al. (1996); 8 – Zygelman et al. (1989), scaled by D reduced mass; 9 – As ref. 6, but scaled by D reduced mass; 10 – Savin et al. (2004); 11 – Barlow (1984); 12 – Estimate, based on low-energy extrapolation of cross-section in Wutte et al. (1997); 13 – total rate coefficient from Barlow (1984), branching ratios from Pineau des Forets et al. (1989); 14 – Walmsley, Flower, & Pineau des Forets (2004); 15 – Kimura et al. (1993); 16 – Kimura, Dutta, & Shimakura (1994); 17 – Stancil & Zygelman (1996); 18 – Kimura, Dutta & Shimakura (1994), scaled by D reduced mass; 19 – Stancil & Zygelman (1996), scaled by D reduced mass; 20 – From detailed balance applied to inverse reaction; 21 – Bodo et al. (2001).
Table A5. Chemical processes: radiative attachment and radiative association (RA).

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>Rate coefficient (cm³ s⁻¹)</th>
<th>Notes</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA1</td>
<td>H + e⁻ → H⁺ + γ</td>
<td>( k_{RA1} = \text{dex}[-17.845 + 0.762 \log T + 0.1523(\log T)^2 - 0.03274(\log T)^3 T \leqslant 6000 \text{ K} )</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>RA2</td>
<td>D + e⁻ → D⁺ + γ</td>
<td>( k_{RA2} = k_{RA1} )</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>RA3</td>
<td>H + H⁺ → H₂ + γ</td>
<td>( k_{RA3} = \text{dex}[-19.38 - 1.523 \log T + 1.118(\log T)^2 - 0.1269(\log T)^3 T &gt; 6000 \text{ K} )</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>RA4</td>
<td>H + D⁺ → HD⁺ + γ</td>
<td>( k_{RA4} = 3.9 \times 10^{-12} T_3^{2.8} \exp \left( \frac{20}{T} \right) )</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>RA5</td>
<td>H + D → HD⁺ + γ</td>
<td>( k_{RA5} = 10^{-25} (2.80202 - 6.63067 \log T + 4.75619(\log T)^2 - 1.39325(\log T)^3 - 0.178259(\log T)^4 - 0.00817907(\log T)^5 T &gt; 200 \text{ K} )</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>RA6</td>
<td>H + H₂ → H₂⁺ + γ</td>
<td>( k_{RA6} = 1.5 \times 10^{-17} T_3^{1.8} \exp \left( \frac{20}{T} \right) )</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>RA7</td>
<td>H + HD⁺ → HD₂⁺ + γ</td>
<td>( k_{RA7} = 1.2 \times 10^{-17} T_3^{1.8} \exp \left( \frac{20}{T} \right) )</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>RA8</td>
<td>H + D₂⁺ → HD⁺ + γ</td>
<td>( k_{RA8} = 1.1 \times 10^{-17} T_3^{1.8} \exp \left( \frac{20}{T} \right) )</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>RA9</td>
<td>H + He → HeH⁺ + γ</td>
<td>( k_{RA9} = 4.16 \times 10^{-16} T_5^{-0.37} \exp \left( -\frac{T}{27700} \right) )</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>RA10</td>
<td>H + Li → LiH⁺ + γ</td>
<td>( k_{RA10} = \text{ dex}[-22.4 + 0.999 \log T - 0.351(\log T)^2] )</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>RA11</td>
<td>D + H⁺ → HD⁺ + γ</td>
<td>( k_{RA11} = 3.9 \times 10^{-19} T_3^{1.8} \exp \left( \frac{20}{T} \right) )</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>RA12</td>
<td>D + D⁺ → D₂⁺ + γ</td>
<td>( k_{RA12} = 1.9 \times 10^{-19} T_3^{1.8} \exp \left( \frac{20}{T} \right) )</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>RA13</td>
<td>H + H₂ → H₂⁺ + γ</td>
<td>( k_{RA13} = 7.0 \times 10^{-18} T_3^{1.8} \exp \left( \frac{20}{T} \right) )</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>RA14</td>
<td>D + HD⁺ → HD₂⁺ + γ</td>
<td>( k_{RA14} = 5.2 \times 10^{-18} T_3^{1.8} \exp \left( \frac{20}{T} \right) )</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>RA15</td>
<td>D + D₂⁺ → D₂⁺ + γ</td>
<td>( k_{RA15} = 4.3 \times 10^{-18} T_3^{1.8} \exp \left( \frac{20}{T} \right) )</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>RA16</td>
<td>D + He → HeD⁺ + γ</td>
<td>( k_{RA16} = 5.0 \times 10^{-16} T_5^{-0.37} \exp \left( -\frac{T}{27700} \right) )</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>RA17</td>
<td>D + Li → LiD⁺ + γ</td>
<td>( k_{RA17} = 1.5 \times 10^{-22} T_3^{-0.9} \exp \left( -\frac{T}{27700} \right) )</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>RA18</td>
<td>Ht + H⁺ → Ht⁺ + γ</td>
<td>( k_{RA18} = 1.0 \times 10^{-16} )</td>
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<td>10</td>
</tr>
<tr>
<td>RA19</td>
<td>Ht + D⁺ → Ht⁺ + γ</td>
<td>( k_{RA19} = 1.0 \times 10^{-16} )</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>RA20</td>
<td>Li + H → LiH⁺ + γ</td>
<td>( k_{RA20} = 1.0 \times 10^{-22} )</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>RA21</td>
<td>HD + H⁺ → H₂D⁺ + γ</td>
<td>( k_{RA21} = 1.0 \times 10^{-16} )</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>RA22</td>
<td>HD + D⁺ → HD₂⁺ + γ</td>
<td>( k_{RA22} = 1.0 \times 10^{-16} )</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>RA23</td>
<td>D₂ + H⁺ → D₂H⁺ + γ</td>
<td>( k_{RA23} = 1.0 \times 10^{-16} )</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>RA24</td>
<td>D₂ + D⁺ → D₂⁺ + γ</td>
<td>( k_{RA24} = 1.0 \times 10^{-16} )</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>RA25</td>
<td>He + H⁺ → HeH⁺ + γ</td>
<td>( k_{RA25} = 8.0 \times 10^{-20} T^{-0.24} \exp \left( -\frac{T}{27700} \right) )</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>RA26</td>
<td>He + D⁺ → HeD⁺ + γ</td>
<td>( k_{RA26} = 1.0 \times 10^{-19} T^{-0.24} \exp \left( -\frac{T}{27700} \right) )</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>RA27</td>
<td>He + Ht → HeHt⁺ + γ</td>
<td>( k_{RA27} = 4.76 \times 10^{-20} T_3^{2.82} \exp \left( \frac{20}{T} \right) )</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>RA28</td>
<td>Li + e⁻ → Li⁻ + γ</td>
<td>( k_{RA28} = 6.1 \times 10^{-17} T_5^{0.58} \exp \left( -\frac{T}{17700} \right) )</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>RA29</td>
<td>Li + Ht → LiHt⁺ + γ</td>
<td>( k_{RA29} = 4.8 \times 10^{-14} T^{-0.49} )</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>RA30</td>
<td>Li + D⁺ → LiD⁺ + γ</td>
<td>( k_{RA30} = 6.4 \times 10^{-14} T^{-0.49} )</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>RA31</td>
<td>Li + H → LiH + γ</td>
<td>( k_{RA31} = 10^{-20} \left[ 3.22 + [0.0657(T/1000)^{-2.45} + 6 \times 10^{-3}(T/1000)^{0.837}]^{-1} \right] )</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>RA32</td>
<td>Li + D → LiD + γ</td>
<td>( k_{RA32} = 5.5 \times 10^{-20} T^{-0.28} \exp \left( -\frac{T}{27700} \right) )</td>
<td></td>
<td>9</td>
</tr>
</tbody>
</table>

**Notes:** T is the gas temperature in K, and \( T_3 = T/300 \) K.

**References:** 1 – Wishart (1979); 2 – Ramaker & Peek (1976); 3 – Ramaker & Peek (1976) and Fromhold & Pickett (1978), scaled by D reduced mass; 4 – Dickinson (2005); 5 – Dalgarino & McDowell (1956); 6 – Same as corresponding H reaction, but scaled by D reduced mass; 7 Kraemer, Šipkro & Juřek (1995); 8 – Dalgarino et al. (1996); Gianturco & Gori Giorgi (1996); 9 Stancil et al. (1996), scaled by D reduced mass; 10 – Gerlich & Hornig (1992); 11 – estimate, based on Gerlich & Hornig (1992): highly uncertain; 12 – estimate - see also Section 3.1.11; 13 Juřek, Šipkro & Kraemer (1995); 14 – Stancil et al. (1993); 15 – Ramsbottom et al. (1994); 16 Dalgarino et al. (1996); 17 – Bennett et al. (2003).
### Table A6. Chemical processes: associative detachment, dissociative attachment and associative ionization (AD).

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>Rate coefficient (cm$^3$ s$^{-1}$)</th>
<th>Notes</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD1</td>
<td>H + H$^-$ → Ht + e$^-$</td>
<td>$k_{AD1} = 1.5 \times 10^{-9}T_{300}^{1.0}$</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>AD2</td>
<td>D + H$^-$ → HD + e$^-$</td>
<td>$k_{AD2} = 1.5 \times 10^{-9}T_{300}^{1.0}$</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>AD3</td>
<td>H + D$^-$ → HD + e$^-$</td>
<td>$k_{AD3} = 1.5 \times 10^{-9}T_{300}^{1.0}$</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>AD4</td>
<td>D + D$^-$ → D$_2$ + e$^-$</td>
<td>$k_{AD4} = 1.6 \times 10^{-9}T_{300}^{1.0}$</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>AD5</td>
<td>Ht + e$^-$ → H + H$^-$</td>
<td>$k_{AD5} = 2.7 \times 10^{-8}T_{900}^{-1.27} \exp(-34000/T)$</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>AD6</td>
<td>HD + e$^-$ → H + D$^-$</td>
<td>$k_{AD6} = 1.35 \times 10^{-9}T_{900}^{-1.27} \exp(-43000/T)$</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>AD7</td>
<td>HD + e$^-$ → D + H$^-$</td>
<td>$k_{AD7} = 1.35 \times 10^{-9}T_{900}^{-1.27} \exp(-43000/T)$</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>AD8</td>
<td>D$_2$ + e$^-$ → D + D$^-$</td>
<td>$k_{AD8} = 6.7 \times 10^{-11}T_{900}^{-1.27} \exp(-34000/T)$</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>AD9</td>
<td>H$^+$ + H$^-$ → Htp + e$^-$</td>
<td>$k_{AD9} = 6.9 \times 10^{-9}T_{900}^{-0.35}$</td>
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<td>5</td>
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<tr>
<td></td>
<td></td>
<td>$= 9.6 \times 10^{-7}T_{900}^{-0.90}$</td>
<td>$T \leq 8000$ K</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$= 3.5 \times 10^{-2} \exp(-300k/3)$</td>
<td>$T &gt; 8000$ K</td>
<td></td>
</tr>
<tr>
<td>AD10</td>
<td>H$^+$ + D$^-$ → HD$^+$ + e$^-$</td>
<td>$k_{AD10} = 1.1 \times 10^{-9}T_{300}^{3.4}$</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>AD11</td>
<td>D$^+$ + H$^-$ → HD$^+$ + e$^-$</td>
<td>$k_{AD11} = 1.1 \times 10^{-9}T_{300}^{3.4}$</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>AD12</td>
<td>D$^+$ + D$^-$ → D$_2^+$ + e$^-$</td>
<td>$k_{AD12} = 1.3 \times 10^{-9}T_{300}^{3.4}$</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>AD13</td>
<td>Htp + H$^-$ → H$_2$ + e$^-$</td>
<td>$k_{AD13} = 2.7 \times 10^{-10}T_{900}^{-0.485} \exp(-35000/T)$</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>AD14</td>
<td>Htp + D$^-$ → HD$_2$ + e$^-$</td>
<td>$k_{AD14} = 2.24 \times 10^{-10}T_{900}^{-0.49} \exp(-35000/T)$</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>AD15</td>
<td>HD$^+$ + H$^-$ → H$_2$D$^+$ + e$^-$</td>
<td>$k_{AD15} = 2.9 \times 10^{-10}T_{900}^{-0.485} \exp(-35000/T)$</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>AD16</td>
<td>HD$^+$ + D$^-$ → HD$_2^+$ + e$^-$</td>
<td>$k_{AD16} = 3.7 \times 10^{-10}T_{900}^{-0.485} \exp(-35000/T)$</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>AD17</td>
<td>D$_2^+$ + H$^-$ → HD$_2$ + e$^-$</td>
<td>$k_{AD17} = 3.0 \times 10^{-10}T_{900}^{-0.485} \exp(-35000/T)$</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>AD18</td>
<td>D$_2^+$ + D$^-$ → D$_4^+$ + e$^-$</td>
<td>$k_{AD18} = 3.9 \times 10^{-10}T_{900}^{-0.485} \exp(-35000/T)$</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>AD19</td>
<td>Li + H$^-$ → LiH + e$^-$</td>
<td>$k_{AD19} = 4.0 \times 10^{-10}$</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>AD20</td>
<td>Li + D$^-$ → LiD + e$^-$</td>
<td>$k_{AD20} = 4.0 \times 10^{-10}$</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>AD21</td>
<td>Li$^+$ + H → LiH + e$^-$</td>
<td>$k_{AD21} = 4.0 \times 10^{-10}$</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>AD22</td>
<td>Li$^+$ + D → LiD + e$^-$</td>
<td>$k_{AD22} = 4.0 \times 10^{-10}$</td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

**Notes:** T is the gas temperature in K, and $T_3 = T/300$ K.

**References:** 1 – Launay et al. (1991); 2 – Same as corresponding H reaction, but scaled by D reduced mass; 3 – Schulz & Asundi (1967); 4 – Xu & Fabrikant (2001); 5 – Poulaert et al. (1978); 6 – Naji et al. (1998); 7 – Stancil et al. (1996).
Table A7. Chemical detachment and collisional dissociation (CD).

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>Rate coefficient (cm$^3$ s$^{-1}$)</th>
<th>Notes</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD1</td>
<td>H$^-$ + e$^-$ $\rightarrow$ H + e$^-$ + e$^-$</td>
<td>$k_{CD1} = \exp[-1.801849334 \times 10^1$</td>
<td>$T_e \leq 0.1$ eV</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\times \ln T_e$ $+ 2.36065220 \times 10^6 \times \ln \T_e$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$- 2.82744300 \times 10^{-1} \times (\ln \T_e)^2$</td>
<td></td>
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</tr>
<tr>
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<td>$+ 1.62341664 \times 10^{-2} \times (\ln \T_e)^3$</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>$- 3.35601203 \times 10^{-2} \times (\ln \T_e)^4$</td>
<td></td>
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</tr>
<tr>
<td></td>
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<td>$+ 1.17832978 \times 10^{-2} \times (\ln \T_e)^5$</td>
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<tr>
<td></td>
<td></td>
<td>$- 1.65619470 \times 10^{-3} \times (\ln \T_e)^6$</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>$+ 1.06827520 \times 10^{-4} \times (\ln \T_e)^7$</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>$- 2.63128581 \times 10^{-5} \times (\ln \T_e)^8$</td>
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<tr>
<td>CD2</td>
<td>H$^-$ + H $\rightarrow$ H + H + e$^-$</td>
<td>$k_{CD2} = 2.5634 \times 10^{-9} T_e^{1.78196}$</td>
<td>$T_e &gt; 0.1$ eV</td>
<td>1</td>
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<tr>
<td></td>
<td></td>
<td>$\exp[-2.0372609 \times 10^1$</td>
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<tr>
<td></td>
<td></td>
<td>$\times \ln T_e$ $+ 1.13944933 \times 10^6 \times \ln \T_e$</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>$- 1.4210135 \times 10^{-1} \times (\ln \T_e)^2$</td>
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<tr>
<td></td>
<td></td>
<td>$+ 8.4644554 \times 10^{-3} \times (\ln \T_e)^3$</td>
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<td></td>
<td>$- 1.4327641 \times 10^{-3} \times (\ln \T_e)^4$</td>
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<td></td>
<td>$+ 2.0122503 \times 10^{-4} \times (\ln \T_e)^5$</td>
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<td>$+ 8.6639632 \times 10^{-5} \times (\ln \T_e)^6$</td>
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<td>$- 2.5856097 \times 10^{-6} \times (\ln \T_e)^7$</td>
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<tr>
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<td>$+ 2.4556012 \times 10^{-6} \times (\ln \T_e)^8$</td>
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<td></td>
<td>$- 8.602805 \times 10^{-8} \times (\ln \T_e)^9$</td>
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<tr>
<td>CD3</td>
<td>H$^+$ + D $\rightarrow$ H + D + e$^-$</td>
<td>$k_{CD3} = k_{CD2}$</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>CD4</td>
<td>H$^+$ + He $\rightarrow$ H + He + e$^-$</td>
<td>$k_{CD4} = 4.1 \times 10^{-17} T^{0.5} \exp\left( \frac{-10472}{T_e} \right)$</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>CD5</td>
<td>D$^+$ + e$^-$ $\rightarrow$ D + e$^-$ + e$^-$</td>
<td>$k_{CD5} = k_{CD1}$</td>
<td></td>
<td>2</td>
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<tr>
<td>CD6</td>
<td>D$^+$ + H $\rightarrow$ D + H + e$^-$</td>
<td>$k_{CD6} = k_{CD2}$</td>
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<tr>
<td>CD7</td>
<td>D$^+$ + D $\rightarrow$ D + D + e$^-$</td>
<td>$k_{CD7} = k_{CD2}$</td>
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<tr>
<td>CD8</td>
<td>D$^+$ + He $\rightarrow$ D + He + e$^-$</td>
<td>$k_{CD8} = 1.5 \times 10^{-17} T^{0.5} \exp\left( \frac{-10472}{T_e} \right)$</td>
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<tr>
<td>CD9</td>
<td>Ht + H $\rightarrow$ H + H + H</td>
<td>$k_{CD9} = 6.67 \times 10^{-12} T^{0.5} \exp\left[ -(1 + \frac{63503}{T_e}) \right]$</td>
<td>v=0</td>
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<tr>
<td>CD10</td>
<td>Ht + Ht $\rightarrow$ H + H + Ht</td>
<td>$k_{CD10} = \frac{5.996 \times 10^{-7} T^{0.4881} \exp\left( \frac{-5467.4}{T_e} \right)}{K}$</td>
<td>v=0</td>
<td>6</td>
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<tr>
<td>CD11</td>
<td>Ht + He $\rightarrow$ H + He + He</td>
<td>$k_{CD11} = \exp\left[ -27.029 + 3.801 \log T_e - \frac{29487}{T_e} \right]$</td>
<td>v=0</td>
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<tr>
<td>CD12</td>
<td>Ht + e$^-$ $\rightarrow$ H + e + H$^+$</td>
<td>$k_{CD12} = 4.49 \times 10^{-9} T^{0.115} \exp\left( \frac{-101258}{T_e} \right)$</td>
<td>v=0</td>
<td>8</td>
</tr>
<tr>
<td>CD13</td>
<td>HD + H $\rightarrow$ H + D + H</td>
<td>$k_{CD13} = k_{CD9}$</td>
<td>See §?</td>
<td>2</td>
</tr>
<tr>
<td>CD14</td>
<td>HD + Ht $\rightarrow$ H + D + Ht</td>
<td>$k_{CD14} = k_{CD10}$</td>
<td>See §?</td>
<td>2</td>
</tr>
<tr>
<td>CD15</td>
<td>HD + He $\rightarrow$ H + D + He</td>
<td>$k_{CD15} = k_{CD11}$</td>
<td>See §?</td>
<td>2</td>
</tr>
<tr>
<td>CD16</td>
<td>HD + e$^-$ $\rightarrow$ H + D + e$^-$</td>
<td>$k_{CD16} = 5.09 \times 10^{-9} T^{0.128} \exp\left( \frac{-103358}{T_e} \right)$</td>
<td>v=0</td>
<td>9</td>
</tr>
<tr>
<td>CD17</td>
<td>D$_2$ + H $\rightarrow$ D + D + H</td>
<td>$k_{CD17} = k_{CD9}$</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>CD18</td>
<td>D$_2$ + Ht $\rightarrow$ D + D + Ht</td>
<td>$k_{CD18} = k_{CD10}$</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>CD19</td>
<td>D$_2$ + He $\rightarrow$ D + D + He</td>
<td>$k_{CD19} = k_{CD11}$</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>CD20</td>
<td>D$_2$ + e$^-$ $\rightarrow$ D + D + e$^-$</td>
<td>$k_{CD20} = 8.24 \times 10^{-9} T^{0.163} \exp\left( \frac{-105388}{T_e} \right)$</td>
<td>v=0</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\times \exp\left( \frac{-5.5339.7}{T_e} \right)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD21</td>
<td>LiH$^+$ + D $\rightarrow$ Li$^+$ + H + D</td>
<td>$k_{CD21} = 1.0 \times 10^{-6} \exp\left( \frac{1400}{\ln T_e} \right)$</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>CD22</td>
<td>LiH$^+$ + D $\rightarrow$ Li$^+$ + H$^+$ + D</td>
<td>$k_{CD22} = 1.0 \times 10^{-6} \exp\left( \frac{1400}{\ln T_e} \right)$</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>CD23</td>
<td>LiH$^+$ + D $\rightarrow$ Li$^+$ + H + D$^+$</td>
<td>$k_{CD23} = 1.0 \times 10^{-6} \exp\left( \frac{1400}{\ln T_e} \right)$</td>
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</tr>
<tr>
<td>CD24</td>
<td>LiD$^+$ + D $\rightarrow$ Li$^+$ + D + D</td>
<td>$k_{CD24} = 1.0 \times 10^{-6} \exp\left( \frac{1400}{\ln T_e} \right)$</td>
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<td>11</td>
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<tr>
<td>CD25</td>
<td>LiD$^+$ + D $\rightarrow$ Li$^+$ + D$^+$ + D</td>
<td>$k_{CD25} = 1.0 \times 10^{-6} \exp\left( \frac{1400}{\ln T_e} \right)$</td>
<td></td>
<td>11</td>
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<tr>
<td>CD26</td>
<td>LiH$^+_2$ + Ht $\rightarrow$ Li$^+_2$ + Ht + Ht</td>
<td>$k_{CD26} = 1.0 \times 10^{-6} \exp\left( \frac{1400}{\ln T_e} \right)$</td>
<td></td>
<td>11</td>
</tr>
</tbody>
</table>

Notes: $T$ is the gas temperature in K and $T_e$ is the gas temperature in eV. $K$ is the equilibrium constant relating reactions TB1 and CD9, and reactions TB2 and CD10; its value is given in §?. References: 1 – Janev et al. (1987); 2 – Assumed same as corresponding H reaction; 3 – Huq et al. (1982); 4 – Same as corresponding H reaction, but scaled by D reduced mass; 5 – Mac Low & Shull (1986); 6 – determined from three-body rate coefficient by detailed balance (see Section 3.1.7); 7 – Martin, Keogh, & Mandy (1998); 8 – Dove et al. (1987); 9 – determined from the Walkauskas & Kaufman (1975) rate coefficient for reaction TB3 by detailed balance; 10 – Trevisan & Tennyson (2002a); 11 – Trevisan & Tennyson (2002b); 13 – estimate – see also Section 3.1.11.
<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>Rate coefficient (cm$^3$s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MN1</td>
<td>H$^+$ + H$^-$ → H + H</td>
<td>$k_{MN1} = 2.4 \times 10^{-6}T^{-1/2} (1.0 + 5.0 \times 10^{-5}T)$</td>
</tr>
<tr>
<td>MN2</td>
<td>D$^+$ + H$^-$ → D + H</td>
<td>$k_{MN2} = 1.1 \times k_{MN1}$</td>
</tr>
<tr>
<td>MN3</td>
<td>H$^+$ + D$^-$ → D + H</td>
<td>$k_{MN3} = 1.1 \times k_{MN1}$</td>
</tr>
<tr>
<td>MN4</td>
<td>D$^+$ + D$^-$ → D + D</td>
<td>$k_{MN4} = 1.3 \times k_{MN1}$</td>
</tr>
<tr>
<td>MN5</td>
<td>Htp + H$^-$ → Ht + H</td>
<td>$k_{MN5} = 1.4 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN6</td>
<td>Htp + H$^-$ → H + H + H</td>
<td>$k_{MN6} = 1.4 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN7</td>
<td>Htp + D$^-$ → Ht + D</td>
<td>$k_{MN7} = 1.7 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN8</td>
<td>Htp + D$^-$ → H + H + D</td>
<td>$k_{MN8} = 1.7 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN9</td>
<td>HD$^+$ + H$^-$ → HD + H</td>
<td>$k_{MN9} = 1.5 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN10</td>
<td>HD$^+$ + H$^-$ → D + H + H</td>
<td>$k_{MN10} = 1.5 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN11</td>
<td>HD$^+$ + D$^-$ → HD + D</td>
<td>$k_{MN11} = 1.9 \times 10^{-7}T_3^{-0.5}$</td>
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<tr>
<td>MN12</td>
<td>HD$^+$ + D$^-$ → D + H + D</td>
<td>$k_{MN12} = 1.9 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN13</td>
<td>D$_2^+$ + H$^-$ → D$_2$ + H</td>
<td>$k_{MN13} = 1.5 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN14</td>
<td>D$_2^+$ + H$^-$ → D + D + H</td>
<td>$k_{MN14} = 2.0 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN15</td>
<td>D$_2^+$ + D$^-$ → D$_2$ + D</td>
<td>$k_{MN15} = 2.0 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN16</td>
<td>D$_2^+$ + D$^-$ → D + D + D</td>
<td>$k_{MN16} = 2.0 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN17</td>
<td>H$^+$ + H$^-$ → Ht + H + H</td>
<td>$k_{MN17} = 2.3 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN18</td>
<td>H$^+$ + H$^-$ → Ht + Ht</td>
<td>$k_{MN18} = 2.3 \times 10^{-7}T_3^{-0.5}$</td>
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<tr>
<td>MN19</td>
<td>H$^+$ + D$^-$ → Ht + H + D</td>
<td>$k_{MN19} = 2.9 \times 10^{-7}T_3^{-0.5}$</td>
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<tr>
<td>MN20</td>
<td>H$^+$ + D$^-$ → Ht + HD</td>
<td>$k_{MN20} = 2.9 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN21</td>
<td>H$_2$D$^+$ + H$^-$ → Ht + H + D</td>
<td>$k_{MN21} = 1.6 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN22</td>
<td>H$_2$D$^+$ + H$^-$ → Ht + HD</td>
<td>$k_{MN22} = 1.6 \times 10^{-7}T_3^{-0.5}$</td>
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<tr>
<td>MN23</td>
<td>H$_2$D$^+$ + H$^-$ → HD + H + H</td>
<td>$k_{MN23} = 1.6 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN24</td>
<td>H$_2$D$^+$ + D$^-$ → Ht + D + D</td>
<td>$k_{MN24} = 1.5 \times 10^{-7}T_3^{-0.5}$</td>
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<tr>
<td>MN25</td>
<td>H$_2$D$^+$ + D$^-$ → Ht + D$_2$</td>
<td>$k_{MN25} = 1.5 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN26</td>
<td>H$_2$D$^+$ + D$^-$ → HD + H + D</td>
<td>$k_{MN26} = 1.5 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN27</td>
<td>H$_2$D$^+$ + D$^-$ → HD + HD</td>
<td>$k_{MN27} = 1.5 \times 10^{-7}T_3^{-0.5}$</td>
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<tr>
<td>MN28</td>
<td>HD$_2^+$ + H$^-$ → Ht + D$_2$</td>
<td>$k_{MN28} = 1.2 \times 10^{-7}T_3^{-0.5}$</td>
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<tr>
<td>MN29</td>
<td>HD$_2^+$ + H$^-$ → HD + H + D</td>
<td>$k_{MN29} = 1.2 \times 10^{-7}T_3^{-0.5}$</td>
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<tr>
<td>MN30</td>
<td>HD$_2^+$ + H$^-$ → HD + HD</td>
<td>$k_{MN30} = 1.2 \times 10^{-7}T_3^{-0.5}$</td>
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<tr>
<td>MN31</td>
<td>HD$_2^+$ + H$^-$ → D$_2$ + H + H</td>
<td>$k_{MN31} = 1.2 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN32</td>
<td>HD$_2^+$ + D$^-$ → HD + D + D</td>
<td>$k_{MN32} = 2.1 \times 10^{-7}T_3^{-0.5}$</td>
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<tr>
<td>MN33</td>
<td>HD$_2^+$ + D$^-$ → D$_2$ + H + H</td>
<td>$k_{MN33} = 2.1 \times 10^{-7}T_3^{-0.5}$</td>
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<tr>
<td>MN34</td>
<td>HD$_2^+$ + D$^-$ → D$_2$ + H + D</td>
<td>$k_{MN34} = 2.1 \times 10^{-7}T_3^{-0.5}$</td>
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<tr>
<td>MN35</td>
<td>D$_2^+$ + H$^-$ → HD + D$_2$</td>
<td>$k_{MN35} = 2.4 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN36</td>
<td>D$_2^+$ + H$^-$ → D$_2$ + H + D</td>
<td>$k_{MN36} = 2.4 \times 10^{-7}T_3^{-0.5}$</td>
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<tr>
<td>MN37</td>
<td>D$_2^+$ + D$^-$ → D$_2$ + D + D</td>
<td>$k_{MN37} = 3.3 \times 10^{-7}T_3^{-0.5}$</td>
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<tr>
<td>MN38</td>
<td>D$_2^+$ + D$^-$ → D$_2$ + D$_2$</td>
<td>$k_{MN38} = 3.3 \times 10^{-7}T_3^{-0.5}$</td>
</tr>
<tr>
<td>MN39</td>
<td>Hep + H$^-$ → He + H</td>
<td>$k_{MN39} = 2.32 \times 10^{-7}T_3^{-0.52} \exp \left( \frac{T}{2180} \right)$</td>
</tr>
<tr>
<td>MN40</td>
<td>Hep + D$^-$ → He + D</td>
<td>$k_{MN40} = 3.03 \times 10^{-7}T_3^{-0.52} \exp \left( \frac{T}{2180} \right)$</td>
</tr>
<tr>
<td>MN41</td>
<td>Li$^+$ + H$^-$ → Li + H</td>
<td>$k_{MN41} = 2.93 \times 10^{-7}T_3^{-0.47} \exp \left( \frac{T}{2180} \right)$</td>
</tr>
<tr>
<td>MN42</td>
<td>Li$^+$ + D$^-$ → Li + D</td>
<td>$k_{MN42} = 2.06 \times 10^{-7}T_3^{-0.5} \exp \left( \frac{T}{2180} \right)$</td>
</tr>
<tr>
<td>MN43</td>
<td>Li$^+$ + H$^+$ → Li + H</td>
<td>$k_{MN43} = 1.8 \times 10^{-7}T_3^{-0.47} \exp \left( \frac{T}{2180} \right)$</td>
</tr>
<tr>
<td>MN44</td>
<td>Li$^+$ + D$^+$ → Li + D</td>
<td>$k_{MN44} = 2.06 \times 10^{-7}T_3^{-0.5} \exp \left( \frac{T}{2180} \right)$</td>
</tr>
</tbody>
</table>

**Notes:** $T$ is the gas temperature in K, and $T_3 = T/300$ K. Some of the neutralization reactions listed here also include dissociation or transfer in the process.

**References:** 1 – Croft et al. (1999); 2 – Same as corresponding H reaction, but scaled by D reduced mass; 3 – Dalgarno & Lepp (1987); 4 – Dalgarno & McDowell (1956); 5 – Le Teuff et al. (2000); 6 – As 2, with the additional assumption of equally probable outcomes; 7 – Peart & Hayton (1994).
Table A9. Chemical processes: three-body association (TB).

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>Rate coefficient (cm$^6$ s$^{-1}$)</th>
<th>Ref.</th>
</tr>
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<tbody>
<tr>
<td>TB1</td>
<td>$H + H + H \rightarrow Ht + H$</td>
<td>See §7</td>
<td>—</td>
</tr>
<tr>
<td>TB2</td>
<td>$H + H + H \rightarrow Ht + Ht$</td>
<td>See §7</td>
<td>—</td>
</tr>
<tr>
<td>TB3</td>
<td>$H + H + He \rightarrow Ht + He$</td>
<td>$k_{TB3} = 6.9 \times 10^{-32}T^{-0.4}$</td>
<td>1</td>
</tr>
<tr>
<td>TB4</td>
<td>$H + D + H \rightarrow HD + H$</td>
<td>See §7</td>
<td>—</td>
</tr>
<tr>
<td>TB5</td>
<td>$H + D + Ht \rightarrow HD + Ht$</td>
<td>See §7</td>
<td>—</td>
</tr>
<tr>
<td>TB6</td>
<td>$H + D + He \rightarrow HD + He$</td>
<td>$k_{TB6} = 6.9 \times 10^{-32}T^{-0.4}$</td>
<td>2</td>
</tr>
<tr>
<td>TB7</td>
<td>$D + D + H \rightarrow D_2 + H$</td>
<td>See §7</td>
<td>—</td>
</tr>
<tr>
<td>TB8</td>
<td>$D + D + Ht \rightarrow D_2 + Ht$</td>
<td>See §7</td>
<td>—</td>
</tr>
<tr>
<td>TB9</td>
<td>$D + D + He \rightarrow D_2 + He$</td>
<td>$k_{TB9} = 6.9 \times 10^{-32}T^{-0.4}$</td>
<td>2</td>
</tr>
<tr>
<td>TB10</td>
<td>$H^+ + H + H \rightarrow HtH + H$</td>
<td>$k_{TB10} = 1.203 \times 10^{-29}T^{-1.041}$</td>
<td>3</td>
</tr>
<tr>
<td>TB11</td>
<td>$D^+ + H + H \rightarrow HD^+ + H$</td>
<td>$k_{TB11} = 1.203 \times 10^{-29}T^{-1.041}$</td>
<td>2</td>
</tr>
<tr>
<td>TB12</td>
<td>$H^+ + D + H \rightarrow HD^+ + H$</td>
<td>$k_{TB12} = 1.203 \times 10^{-29}T^{-1.041}$</td>
<td>2</td>
</tr>
<tr>
<td>TB13</td>
<td>$D^+ + D + H \rightarrow D_2^+ + H$</td>
<td>$k_{TB13} = 1.203 \times 10^{-29}T^{-1.041}$</td>
<td>2</td>
</tr>
<tr>
<td>TB14</td>
<td>$H^+ + Ht + H \rightarrow H_3^+ + H$</td>
<td>$k_{TB14} = 1.0 \times 10^{-28}$</td>
<td>4</td>
</tr>
<tr>
<td>TB15</td>
<td>$H^+ + Ht + Ht \rightarrow H_3^+ + Ht$</td>
<td>$k_{TB15} = 5.4 \times 10^{-29}$</td>
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<tr>
<td>TB16</td>
<td>$H^+ + Ht + He \rightarrow H_3^+ + He$</td>
<td>$k_{TB16} = 1.07 \times 10^{-28}$</td>
<td>5</td>
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<tr>
<td>TB17</td>
<td>$D^+ + Ht + H \rightarrow H_2D^+ + H$</td>
<td>$k_{TB17} = 1.0 \times 10^{-28}$</td>
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<td>TB18</td>
<td>$D^+ + Ht + Ht \rightarrow H_2D^+ + Ht$</td>
<td>$k_{TB18} = 5.4 \times 10^{-29}$</td>
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<td>TB19</td>
<td>$D^+ + Ht + He \rightarrow H_2D^+ + He$</td>
<td>$k_{TB19} = 1.07 \times 10^{-28}$</td>
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<td>TB20</td>
<td>$H^+ + HD + H \rightarrow H_2D^+ + H$</td>
<td>$k_{TB20} = 1.0 \times 10^{-28}$</td>
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<td>TB21</td>
<td>$H^+ + HD + Ht \rightarrow H_2D^+ + Ht$</td>
<td>$k_{TB21} = 5.4 \times 10^{-29}$</td>
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<td>TB22</td>
<td>$H^+ + HD + He \rightarrow H_2D^+ + He$</td>
<td>$k_{TB22} = 1.07 \times 10^{-28}$</td>
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<td>TB23</td>
<td>$D^+ + HD + H \rightarrow HD_2^+ + H$</td>
<td>$k_{TB23} = 1.0 \times 10^{-28}$</td>
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<td>TB24</td>
<td>$D^+ + HD + Ht \rightarrow HD_2^+ + Ht$</td>
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<td>TB25</td>
<td>$D^+ + HD + He \rightarrow HD_2^+ + He$</td>
<td>$k_{TB25} = 1.07 \times 10^{-28}$</td>
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<td>TB26</td>
<td>$H^+ + D_2 + H \rightarrow HD_2^+ + H$</td>
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<tr>
<td>TB27</td>
<td>$H^+ + D_2 + Ht \rightarrow HD_2^+ + Ht$</td>
<td>$k_{TB27} = 5.4 \times 10^{-29}$</td>
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<td>TB28</td>
<td>$H^+ + D_2 + He \rightarrow HD_2^+ + He$</td>
<td>$k_{TB28} = 1.07 \times 10^{-28}$</td>
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<tr>
<td>TB29</td>
<td>$D^+ + D_2 + H \rightarrow D_3^+ + H$</td>
<td>$k_{TB29} = 1.0 \times 10^{-28}$</td>
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<tr>
<td>TB30</td>
<td>$D^+ + D_2 + Ht \rightarrow D_3^+ + Ht$</td>
<td>$k_{TB30} = 5.4 \times 10^{-29}$</td>
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<tr>
<td>TB31</td>
<td>$D^+ + D_2 + He \rightarrow D_3^+ + He$</td>
<td>$k_{TB31} = 1.07 \times 10^{-28}$</td>
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<tr>
<td>TB32</td>
<td>$Li + H + H \rightarrow LiH + H$</td>
<td>$k_{TB32} = 2.5 \times 10^{-29}T^{-1}$</td>
<td>6</td>
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<tr>
<td>TB33</td>
<td>$Li + H + Ht \rightarrow LiH + Ht$</td>
<td>$k_{TB33} = 4.1 \times 10^{-30}T^{-1}$</td>
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<td>TB34</td>
<td>$Li + D + H \rightarrow LiD + H$</td>
<td>$k_{TB34} = 2.5 \times 10^{-29}T^{-1}$</td>
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<tr>
<td>TB35</td>
<td>$Li + D + Ht \rightarrow LiD + Ht$</td>
<td>$k_{TB35} = 4.1 \times 10^{-30}T^{-1}$</td>
<td>2</td>
</tr>
</tbody>
</table>

Notes: $T$ is the gas temperature in K.

### Table A10. Chemical processes: isotopic exchange (IX).

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>Rate coefficient (cm³ s⁻¹)</th>
<th>Notes</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IX1</td>
<td>Ht + D → HD⁺ + H</td>
<td>(k_{\text{IX1}} = 1.07 \times 10^{-9}T^{0.062} \exp \left( \frac{-T}{41000} \right) )</td>
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<tr>
<td>IX2</td>
<td>Ht + D → HD + H⁺</td>
<td>(k_{\text{IX2}} = 1.0 \times 10^{-9} )</td>
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<td>IX3</td>
<td>HD⁺ + H → Ht + D</td>
<td>(k_{\text{IX3}} = 1.0 \times 10^{-9} \exp \left( -\frac{154}{T} \right) )</td>
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<tr>
<td>IX4</td>
<td>HD⁺ + H → Ht + D⁺</td>
<td>(k_{\text{IX4}} = 1.0 \times 10^{-9} )</td>
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<td>IX5</td>
<td>HD⁺ + D → D₂⁺ + H</td>
<td>(k_{\text{IX5}} = 1.0 \times 10^{-9} )</td>
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<td>IX6</td>
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<td>IX7</td>
<td>D₂⁺ + H → HD⁺ + D</td>
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<td>D₂⁺ + H → HD + D⁺</td>
<td>(k_{\text{IX8}} = 1.0 \times 10^{-9} )</td>
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<tr>
<td>IX9</td>
<td>Ht + D⁺ → HD⁺ + H</td>
<td>(k_{\text{IX9}} = 4.17 \times 10^{-10} + 8.46 \times 10^{-10} \log T )</td>
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<tr>
<td>IX10</td>
<td>Ht + D⁺ → HD⁺ + H</td>
<td>(k_{\text{IX10}} = [1.04 \times 10^{-9} + 9.52 \times 10^{-9} \left( \frac{T}{10000} \right)] )</td>
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<tr>
<td>IX11</td>
<td>HD + H⁺ → Ht + D⁺</td>
<td>(k_{\text{IX11}} = 1.1 \times 10^{-9} \exp \left( -\frac{440}{T} \right) )</td>
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<tr>
<td>IX12</td>
<td>HD + H⁺ → Ht + D</td>
<td>(k_{\text{IX12}} = 1.0 \times 10^{-9} \exp \left( -\frac{21000}{T} \right) )</td>
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<td>IX13</td>
<td>HD + D⁺ → D₂ + H⁺</td>
<td>(k_{\text{IX13}} = 1.0 \times 10^{-9} )</td>
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<tr>
<td>IX14</td>
<td>HD + D⁺ → D₂⁺ + H</td>
<td>(k_{\text{IX14}} = [3.54 \times 10^{-9} + 7.50 \times 10^{-10} \left( \frac{T}{10000} \right)] )</td>
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<td>IX16</td>
<td>D₂ + H⁺ → HD⁺ + D</td>
<td>(k_{\text{IX16}} = [5.18 \times 10^{-11} + 3.05 \times 10^{-9} \left( \frac{T}{10000} \right)] )</td>
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<tr>
<td>IX17</td>
<td>Ht + D → HD + H</td>
<td>(k_{\text{IX17}} = \text{dex} \left[ -56.4737 + 5.88886 \log T \right] + 7.19692(\log T)^2 + 2.25906(\log T)^4 - 2.16903(\log T)^6 + 0.317887(\log T)^7 )</td>
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<tr>
<td>IX18</td>
<td>HD + H → Ht + D</td>
<td>(k_{\text{IX18}} = 5.25 \times 10^{-11} \exp \left( -\frac{440}{T} \right) )</td>
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<tr>
<td>IX19</td>
<td>HD + D → D₂ + H</td>
<td>(k_{\text{IX19}} = 1.15 \times 10^{-11} \exp \left( -\frac{420}{T} \right) )</td>
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<td>IX20</td>
<td>D₂ + H → HD + D</td>
<td>(k_{\text{IX20}} = \text{dex} \left[ 10 + 10 \log T \right] + 33.5707(\log T)^2 - 13.0449(\log T)^4 + 1.22017(\log T)^6 + 0.0482453(\log T)^7 )</td>
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<td>IX21</td>
<td>H₂⁺ + D → H₂D⁺ + H</td>
<td>(k_{\text{IX21}} = 1.0 \times 10^{-9} )</td>
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<td>IX22</td>
<td>H₂D⁺ + H → H₂⁺ + H</td>
<td>(k_{\text{IX22}} = 1.0 \times 10^{-9} \exp \left( -\frac{62}{T} \right) )</td>
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<td>H₂D⁺ + D → HD⁺ + H</td>
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<td>HD⁺ + H → H₂D⁺ + D</td>
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<td>H₂⁺ + HD → H₂D⁺ + Ht</td>
<td>(k_{\text{IX27}} = 3.5 \times 10^{-10} )</td>
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<td>IX28</td>
<td>H₂⁺ + D₂ → H₂D⁺ + HD</td>
<td>(k_{\text{IX28}} = 3.5 \times 10^{-11} \exp \left( -\frac{30}{T} \right) )</td>
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<td>IX29</td>
<td>H₂⁺ + H → HD⁺ + Ht</td>
<td>(k_{\text{IX29}} = 9.64 \times 10^{-10} \exp \left( -\frac{0.024}{T} \right) )</td>
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<tr>
<td>IX30</td>
<td>H₂D⁺ + Ht → H₂⁺ + HD</td>
<td>(k_{\text{IX30}} = 1.4 \times 10^{-10} \exp \left( -\frac{22}{T} \right) )</td>
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<td>IX31</td>
<td>H₂D⁺ + HD → H₂⁺ + D₂</td>
<td>(k_{\text{IX31}} = 1.75 \times 10^{-11} \exp \left( -\frac{152}{T} \right) )</td>
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<td>H₂D⁺ + HD → HD⁺ + Ht</td>
<td>(k_{\text{IX32}} = 2.6 \times 10^{-10} )</td>
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<td>IX33</td>
<td>H₂D⁺ + D₂ → HD⁺ + Ht</td>
<td>(k_{\text{IX33}} = 8.5 \times 10^{-10} )</td>
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<td>IX34</td>
<td>H₂D⁺ + D₂ → D₂⁺ + Ht</td>
<td>(k_{\text{IX34}} = 8.5 \times 10^{-10} )</td>
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<tr>
<td>IX35</td>
<td>HD⁺ + Ht → H₂⁺ + D₂</td>
<td>(k_{\text{IX35}} = 2.0 \times 10^{-10} \exp \left( -\frac{240}{T} \right) )</td>
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</table>
### Table A10 – continued

<table>
<thead>
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<th>No.</th>
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<th>Rate coefficient (cm$^3$ s$^{-1}$)</th>
<th>Notes</th>
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<td>IX36</td>
<td>HD$_2^+$ + Ht $\rightarrow$ H$_2$D$^+$ + HD</td>
<td>$k_{\text{IX36}} = 1.0 \times 10^{-10} \exp \left(-\frac{187.2}{T_3}\right)$</td>
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<td>IX38</td>
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<td>IX39</td>
<td>HD$_2^+$ + D$_2$ $\rightarrow$ D$_3^+$ + HD</td>
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<td>IX40</td>
<td>D$_3^+$ + Ht $\rightarrow$ H$_2$D$^+$ + D$_2$</td>
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<td>$k_{\text{IX41}} = 1.5 \times 10^{-9} \exp \left(-\frac{231.8}{T_3}\right)$</td>
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<td>HeH$^+$ + D $\rightarrow$ HeD$^+$ + H</td>
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<td>IX44</td>
<td>HeD$^+$ + H $\rightarrow$ HeH$^+$ + D</td>
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<td>IX45</td>
<td>LiH$^+$ + D $\rightarrow$ LiD$^+$ + H</td>
<td>$k_{\text{IX45}} = 1.0 \times 10^{-9}$</td>
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<td>IX46</td>
<td>LiD$^+$ + H $\rightarrow$ LiH$^+$ + D</td>
<td>$k_{\text{IX46}} = 1.0 \times 10^{-9} \exp \left(-\frac{64}{T_3}\right)$</td>
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**Notes:** T is the gas temperature in K, and $T_3 = T/300$ K.

**References:**
<table>
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<th>No.</th>
<th>Reaction</th>
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<td>Htp + H$_3$ + H</td>
<td>$k_{TR1} = 2.24 \times 10^{-9} T_3^{0.642} \exp\left(-\frac{T}{3000}\right)$</td>
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<td>Htp + HD + H$_3$ + D</td>
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<td>TR3</td>
<td>Htp + HD + H$_2$D$^+$ + H</td>
<td>$k_{TR3} = 1.05 \times 10^{-9}$</td>
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<td>TR4</td>
<td>Htp + D$_2$ + H$_2$D$^+$ + D</td>
<td>$k_{TR4} = 1.05 \times 10^{-9}$</td>
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<tr>
<td>TR5</td>
<td>Htp + D$_2$ + HD$^+$ + H</td>
<td>$k_{TR5} = 1.05 \times 10^{-9}$</td>
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<td>TR6</td>
<td>HD$^+$ + H$_2$ + D</td>
<td>$k_{TR6} = 0.5 \times k_{TR1}$</td>
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<td>TR7</td>
<td>HD$^+$ + H$_2$D$^+$ + H</td>
<td>$k_{TR7} = 0.5 \times k_{TR1}$</td>
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<td>$k_{TR8} = 1.05 \times 10^{-9}$</td>
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<td>$k_{TR9} = 1.05 \times 10^{-9}$</td>
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<td>HD$^+$ + D$_2$ + HD$^+$ + D</td>
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<td>$k_{TR12} = 1.05 \times 10^{-9}$</td>
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<td>D$_2$ + H$_2$ + HD$^+$ + H</td>
<td>$k_{TR13} = 1.05 \times 10^{-9}$</td>
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<td>TR14</td>
<td>D$_2$ + HD + HD$^+$ + H</td>
<td>$k_{TR14} = 1.05 \times 10^{-9}$</td>
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<td>TR15</td>
<td>D$_2$ + HD + D$_2$ + H$_2$ + H</td>
<td>$k_{TR15} = 1.05 \times 10^{-9}$</td>
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<tr>
<td>TR16</td>
<td>D$_2$ + D$_2$ + D$_2$ + D</td>
<td>$k_{TR16} = 2.1 \times 10^{-9}$</td>
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<tr>
<td>TR17</td>
<td>H$_2$ + H + Htp + H</td>
<td>$k_{TR17} = 7.7 \times 10^{-9} \exp\left(-\frac{17560}{T}\right)$</td>
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<td>TR18</td>
<td>H$_2$ + D + Htp + HD</td>
<td>$k_{TR18} = 0.5 \times k_{TR17}$</td>
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<td>TR19</td>
<td>H$_2$ + D + HD$^+$ + H</td>
<td>$k_{TR19} = 0.5 \times k_{TR17}$</td>
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<td>H$_2$D$^+$ + H + Htp + HD</td>
<td>$k_{TR20} = 0.5 \times k_{TR17}$</td>
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<td>H$_2$D$^+$ + H + HD$^+$ + Htp + HD</td>
<td>$k_{TR21} = 0.5 \times k_{TR17}$</td>
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<tr>
<td>TR22</td>
<td>H$_2$D$^+$ + D + Htp + D$_2$</td>
<td>$k_{TR22} = 0.333 \times k_{TR17}$</td>
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<td>TR23</td>
<td>H$_2$D$^+$ + D + HD$^+$ + HD</td>
<td>$k_{TR23} = 0.333 \times k_{TR17}$</td>
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<td>H$_2$D$^+$ + D + D$_2$ + Htp</td>
<td>$k_{TR24} = 0.333 \times k_{TR17}$</td>
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<td>H$_2$D$^+$ + H + Htp + D$_2$</td>
<td>$k_{TR25} = 0.333 \times k_{TR17}$</td>
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<td>H$_2$D$^+$ + H + D$_2$ + Htp</td>
<td>$k_{TR27} = 0.333 \times k_{TR17}$</td>
</tr>
<tr>
<td>TR28</td>
<td>H$_2$D$^+$ + D + HD$^+$ + HD</td>
<td>$k_{TR28} = 0.5 \times k_{TR17}$</td>
</tr>
<tr>
<td>TR29</td>
<td>H$_2$D$^+$ + D + D$_2$ + HD</td>
<td>$k_{TR29} = 0.5 \times k_{TR17}$</td>
</tr>
<tr>
<td>TR30</td>
<td>D$_2$ + H + HD$^+$ + HD</td>
<td>$k_{TR30} = 0.5 \times k_{TR17}$</td>
</tr>
<tr>
<td>TR31</td>
<td>D$_2$ + H + D$_2$ + HD</td>
<td>$k_{TR31} = 0.5 \times k_{TR17}$</td>
</tr>
<tr>
<td>TR32</td>
<td>D$_2$ + D + D$_2$ + D$_2$</td>
<td>$k_{TR32} = k_{TR17}$</td>
</tr>
<tr>
<td>TR33</td>
<td>He + Htp + He + He</td>
<td>$k_{TR33} = 3.0 \times 10^{-10} \exp\left(-\frac{6217}{T}\right)$</td>
</tr>
<tr>
<td>TR34</td>
<td>He + HD$^+$ + He + HD$^+$</td>
<td>$k_{TR34} = k_{TR33}$</td>
</tr>
<tr>
<td>TR35</td>
<td>He + HD$^+$ + HD$^+$ + HD</td>
<td>$k_{TR35} = k_{TR33}$</td>
</tr>
<tr>
<td>TR36</td>
<td>He + D$_2$ + He + HD$^+$ + HD</td>
<td>$k_{TR36} = k_{TR33}$</td>
</tr>
<tr>
<td>TR37</td>
<td>HeH$^+$ + H + Htp + He</td>
<td>$k_{TR37} = 1.04 \times 10^{-9} T_3^{0.13} \exp\left(-\frac{T}{3000}\right)$</td>
</tr>
<tr>
<td>TR38</td>
<td>HeH$^+$ + D + HD$^+$ + He</td>
<td>$k_{TR38} = 8.5 \times 10^{-10} T_3^{13} \exp\left(-\frac{T}{3000}\right)$</td>
</tr>
<tr>
<td>TR39</td>
<td>HeH$^+$ + H + H$_2$ + He</td>
<td>$k_{TR39} = 1.53 \times 10^{-9} T_3^{24} \exp\left(-\frac{T}{3000}\right)$</td>
</tr>
<tr>
<td>TR40</td>
<td>HeH$^+$ + HD + H$_2$D$^+$ + He</td>
<td>$k_{TR40} = 1.20 \times 10^{-9} T_3^{24} \exp\left(-\frac{T}{3000}\right)$</td>
</tr>
<tr>
<td>TR41</td>
<td>HeH$^+$ + D$_2$ + HD$^+$ + He</td>
<td>$k_{TR41} = 1.1 \times 10^{-9} T_3^{24} \exp\left(-\frac{T}{3000}\right)$</td>
</tr>
<tr>
<td>TR42</td>
<td>HeH$^+$ + D + HD$^+$ + He</td>
<td>$k_{TR42} = 9.1 \times 10^{-10} T_3^{13} \exp\left(-\frac{T}{3000}\right)$</td>
</tr>
<tr>
<td>TR43</td>
<td>HeH$^+$ + D + D$_2$ + He</td>
<td>$k_{TR43} = 8.5 \times 10^{-10} T_3^{13} \exp\left(-\frac{T}{3000}\right)$</td>
</tr>
<tr>
<td>TR44</td>
<td>HeH$^+$ + H + H$_2$D$^+$ + He</td>
<td>$k_{TR44} = 1.24 \times 10^{-9} T_3^{24} \exp\left(-\frac{T}{3000}\right)$</td>
</tr>
<tr>
<td>TR45</td>
<td>HeH$^+$ + HD + HD$^+$ + He</td>
<td>$k_{TR45} = 1.2 \times 10^{-9} T_3^{24} \exp\left(-\frac{T}{3000}\right)$</td>
</tr>
<tr>
<td>TR46</td>
<td>HeH$^+$ + D$_2$ + D$_2$ + He</td>
<td>$k_{TR46} = 1.1 \times 10^{-9} T_3^{24} \exp\left(-\frac{T}{3000}\right)$</td>
</tr>
<tr>
<td>TR47</td>
<td>LiH$^+$ + H + Li$^+$ + Htp</td>
<td>$k_{TR47} = 3.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>TR48</td>
<td>LiH$^+$ + D + Li$^+$ + HD</td>
<td>$k_{TR48} = 3.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>TR49</td>
<td>LiD$^+$ + H + Li$^+$ + HD</td>
<td>$k_{TR49} = 3.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>TR50</td>
<td>LiD$^+$ + D + Li$^+$ + D$_2$</td>
<td>$k_{TR50} = 3.0 \times 10^{-10}$</td>
</tr>
<tr>
<td>TR51</td>
<td>LiH$^+$ + H + Li + Htp</td>
<td>$k_{TR51} = 9.0 \times 10^{-10} \exp\left(-\frac{66400}{T}\right)$</td>
</tr>
<tr>
<td>TR52</td>
<td>LiH$^+$ + D + Li + HD$^+$</td>
<td>$k_{TR52} = k_{TR51}$</td>
</tr>
<tr>
<td>TR53</td>
<td>LiD$^+$ + H + Li + HD$^+$</td>
<td>$k_{TR53} = k_{TR51}$</td>
</tr>
<tr>
<td>TR54</td>
<td>LiD$^+$ + D + Li + D$_2$</td>
<td>$k_{TR54} = k_{TR51}$</td>
</tr>
<tr>
<td>No.</td>
<td>Reaction</td>
<td>Rate coefficient (cm$^3$ s$^{-1}$)</td>
</tr>
<tr>
<td>-----</td>
<td>----------------------------------------------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>TR55</td>
<td>LiH + H$^+$ → Li$^+$ + Ht</td>
<td>$k_{TR55} = 2.0 \times 10^{-15}$</td>
</tr>
<tr>
<td>TR56</td>
<td>LiH + D$^+$ → Li$^+$ + HD</td>
<td>$k_{TR56} = 2.0 \times 10^{-15}$</td>
</tr>
<tr>
<td>TR57</td>
<td>LiD + H$^+$ → Li$^+$ + HD</td>
<td>$k_{TR57} = 2.0 \times 10^{-15}$</td>
</tr>
<tr>
<td>TR58</td>
<td>LiD + D$^+$ → Li$^+$ + D$_2$</td>
<td>$k_{TR58} = 2.0 \times 10^{-15}$</td>
</tr>
<tr>
<td>TR59</td>
<td>LiH + H$^+$ → Li + Htp</td>
<td>$k_{TR59} = 1.0 \times 10^{-9}$</td>
</tr>
<tr>
<td>TR60</td>
<td>LiH + D$^+$ → Li + HD$^+$</td>
<td>$k_{TR60} = 1.0 \times 10^{-9}$</td>
</tr>
<tr>
<td>TR61</td>
<td>LiD + H$^+$ → Li + HD$^+$</td>
<td>$k_{TR61} = 1.0 \times 10^{-9}$</td>
</tr>
<tr>
<td>TR62</td>
<td>LiD + D$^+$ → Li + D$_2^+$</td>
<td>$k_{TR62} = 1.0 \times 10^{-9}$</td>
</tr>
<tr>
<td>TR63</td>
<td>LiH + H → Li + Ht</td>
<td>$k_{TR63} = 1.55 \times 10^{-11}\tau^{0.4247}$</td>
</tr>
<tr>
<td>TR64</td>
<td>LiH + D → Li + HD</td>
<td>$k_{TR64} = 1.2 \times 10^{-11}\tau^{0.4247}$</td>
</tr>
<tr>
<td>TR65</td>
<td>LiD + H → Li + IID</td>
<td>$k_{TR65} = 1.54 \times 10^{-11}\tau^{0.4247}$</td>
</tr>
<tr>
<td>TR66</td>
<td>LiD + D → Li + D$_2$</td>
<td>$k_{TR66} = 1.2 \times 10^{-11}\tau^{0.4247}$</td>
</tr>
</tbody>
</table>

Notes: $T$ is the gas temperature in K, and $T_3 = T/300$ K.

References: 1 – Linder, Janev & Botero (1995); 2 – Stancil et al. (1998); 3 – Walmsley, Flower & Pineau des Forêts (2004); 4 – Sidhu, Miller & Tennyson (1992); 5 – estimate, based on Sidhu, Miller & Tennyson (1992); 6 – Black (1978); 7 – Stancil et al. (1998), based on Black (1978); 8 – estimate, based on Black (1978); 9 – Linder, Janev & Botero (1995), scaled as in Stancil et al. (1998); 10 – Estimate, based on Stancil et al. (1998); 11 – Same as corresponding H reaction, but scaled by D reduced mass; 12 – Stancil et al. (1996); 13 – Stancil et al. (1998), based on corresponding H reaction in Stancil et al. (1996); 14 – estimate, based on Stancil et al. (1996); 15 – Bodo et al. (2001); 16 – same as corresponding H reaction; 17 – Defazio et al. (2005).
Table A12. Chemical processes: background radiation induced photodetachment, photodissociation and photoionization (BP).

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>Rate ($J_{21}^{-1}$ s$^{-1}$)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP1</td>
<td>H$^-$ + γ → H + e$^-$</td>
<td>$R_{BP1} = 1.36 \times 10^{-11}$</td>
<td>1</td>
</tr>
<tr>
<td>BP2</td>
<td>D$^-$ + γ → D + e$^-$</td>
<td>$R_{BP2} = 1.36 \times 10^{-11}$</td>
<td>2</td>
</tr>
<tr>
<td>BP3</td>
<td>Htp + γ → H + H$^+$</td>
<td>$R_{BP3} = 4.11 \times 10^{-12}$</td>
<td>3</td>
</tr>
<tr>
<td>BP4</td>
<td>HD$^+$ + γ → H + D$^+$</td>
<td>$R_{BP4} = 2.05 \times 10^{-12}$</td>
<td>2</td>
</tr>
<tr>
<td>BP5</td>
<td>HD$^+$ + γ → D + H$^+$</td>
<td>$R_{BP5} = 2.05 \times 10^{-12}$</td>
<td>2</td>
</tr>
<tr>
<td>BP6</td>
<td>D$^+_2$ + γ → D + D$^+$</td>
<td>$R_{BP6} = 4.11 \times 10^{-12}$</td>
<td>2</td>
</tr>
<tr>
<td>BP7</td>
<td>Ht + γ → H + H</td>
<td>$R_{BP7} = 1.3 \times 10^{-12} f_{sh, Ht}$</td>
<td>5</td>
</tr>
<tr>
<td>BP8</td>
<td>HD + γ → H + D</td>
<td>$R_{BP8} = 1.45 \times 10^{-12} f_{sh, HD}$</td>
<td>6</td>
</tr>
<tr>
<td>BP9</td>
<td>D$_2$ + γ → D + D</td>
<td>$R_{BP9} = 1.3 \times 10^{-12}$</td>
<td>7</td>
</tr>
<tr>
<td>BP10</td>
<td>H$_2^+$ + γ → Htp + H</td>
<td>$R_{BP10} = 2.4 \times 10^{-16}$</td>
<td>8</td>
</tr>
<tr>
<td>BP11</td>
<td>H$_2^+$ + γ → Ht + H$^+$</td>
<td>$R_{BP11} = 2.4 \times 10^{-16}$</td>
<td>8</td>
</tr>
<tr>
<td>BP12</td>
<td>H$_2$D$^+$ + γ → Htp + D</td>
<td>$R_{BP12} = 1.2 \times 10^{-16}$</td>
<td>9</td>
</tr>
<tr>
<td>BP13</td>
<td>H$_2$D$^+$ + γ → Ht + D$^+$</td>
<td>$R_{BP13} = 1.2 \times 10^{-16}$</td>
<td>9</td>
</tr>
<tr>
<td>BP14</td>
<td>H$_3$D$^+$ + γ → HD$^+$ + H</td>
<td>$R_{BP14} = 1.2 \times 10^{-16}$</td>
<td>9</td>
</tr>
<tr>
<td>BP15</td>
<td>H$_3$D$^+$ + γ → HD + H$^+$</td>
<td>$R_{BP15} = 1.2 \times 10^{-16}$</td>
<td>9</td>
</tr>
<tr>
<td>BP16</td>
<td>HD$_2^+$ + γ → HD$^+$ + D</td>
<td>$R_{BP16} = 1.2 \times 10^{-16}$</td>
<td>9</td>
</tr>
<tr>
<td>BP17</td>
<td>HD$_2^+$ + γ → HD + D$^+$</td>
<td>$R_{BP17} = 1.2 \times 10^{-16}$</td>
<td>9</td>
</tr>
<tr>
<td>BP18</td>
<td>HD$_2^+$ + γ → D$_2^+$ + H</td>
<td>$R_{BP18} = 1.2 \times 10^{-16}$</td>
<td>9</td>
</tr>
<tr>
<td>BP19</td>
<td>HD$_2^+$ + γ → D$_2$ + H$^+$</td>
<td>$R_{BP19} = 1.2 \times 10^{-16}$</td>
<td>9</td>
</tr>
<tr>
<td>BP20</td>
<td>D$_2^+$ + γ → D$_2^+$ + D</td>
<td>$R_{BP20} = 2.4 \times 10^{-16}$</td>
<td>9</td>
</tr>
<tr>
<td>BP21</td>
<td>D$_2^+$ + γ → D$_2$ + D$^+$</td>
<td>$R_{BP21} = 2.4 \times 10^{-16}$</td>
<td>9</td>
</tr>
<tr>
<td>BP22</td>
<td>HeH$^+$ + γ → He + H$^+$</td>
<td>$R_{BP22} = 1.0 \times 10^{-17}$</td>
<td>10</td>
</tr>
<tr>
<td>BP23</td>
<td>HeD$^+$ + γ → He + D$^+$</td>
<td>$R_{BP23} = 1.0 \times 10^{-17}$</td>
<td>10</td>
</tr>
<tr>
<td>BP24</td>
<td>He$_2^+$ + γ → He + He$^+$</td>
<td>$R_{BP24} = 1.0 \times 10^{-17}$</td>
<td>10</td>
</tr>
<tr>
<td>BP25</td>
<td>Li + γ → Li$^+$ + e$^-$</td>
<td>$R_{BP25} = 1.4 \times 10^{-12}$</td>
<td>12</td>
</tr>
<tr>
<td>BP26</td>
<td>Li + γ → Li + e$^-$</td>
<td>$R_{BP26} = 1.2 \times 10^{-11}$</td>
<td>13</td>
</tr>
<tr>
<td>BP27</td>
<td>LiH$^+$ + γ → Li$^+$ + H</td>
<td>$R_{BP27} = 5.0 \times 10^{-18}$</td>
<td>13</td>
</tr>
<tr>
<td>BP28</td>
<td>LiH$^+$ + γ → Li + H$^+$</td>
<td>$R_{BP28} = 9.3 \times 10^{-9}$</td>
<td>13</td>
</tr>
<tr>
<td>BP29</td>
<td>LiD$^+$ + γ → Li$^+$ + D</td>
<td>$R_{BP29} = 5.0 \times 10^{-18}$</td>
<td>2</td>
</tr>
<tr>
<td>BP30</td>
<td>LiD$^+$ + γ → Li + D$^+$</td>
<td>$R_{BP30} = 9.3 \times 10^{-9}$</td>
<td>2</td>
</tr>
<tr>
<td>BP31</td>
<td>LiH + γ → Li + H</td>
<td>$R_{BP31} = 4.4 \times 10^{-14}$</td>
<td>14</td>
</tr>
<tr>
<td>BP32</td>
<td>LiD + γ → Li + D</td>
<td>$R_{BP32} = 4.4 \times 10^{-14}$</td>
<td>2</td>
</tr>
</tbody>
</table>

Notes: γ represents a photon from the external background radiation field. The listed reaction rates were computed assuming that this background has the spectrum of a $10^5$ K diluted black-body, cut-off above $h\nu = 13.6$ eV, as described in Section 3. With this spectrum, reactions with threshold energies greater than 13.6 eV do not occur and are not listed in the table. $f_{sh, H}$ and $f_{sh, HD}$ are the self-shielding factors for Ht and HD photodissociation, respectively (see e.g. Glover & Jappsen 2007). Note that in this paper, we consider only the limiting cases $f_{sh, H} = f_{sh, HD} = 0$ and $f_{sh, H} = f_{sh, HD} = 1$.

Table A13. Chemical processes: cosmic ray ionization (CR).

<table>
<thead>
<tr>
<th>No.</th>
<th>Process</th>
<th>Rate ($\zeta_i/\zeta_H$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR1</td>
<td>$H + C.R. \rightarrow H^+ + e^-$</td>
<td>1.0</td>
<td>--</td>
</tr>
<tr>
<td>CR2</td>
<td>$Ht + C.R. \rightarrow Ht^+ + e^-$</td>
<td>2.09</td>
<td>1</td>
</tr>
<tr>
<td>CR3</td>
<td>$Ht + C.R. \rightarrow H + H^+ + e^-$</td>
<td>0.09</td>
<td>1</td>
</tr>
<tr>
<td>CR4</td>
<td>$Ht + C.R. \rightarrow H + H$</td>
<td>3.26</td>
<td>1</td>
</tr>
<tr>
<td>CR5</td>
<td>$He + C.R. \rightarrow He^+ + e^-$</td>
<td>1.09</td>
<td>1</td>
</tr>
<tr>
<td>CR6</td>
<td>$D + C.R. \rightarrow D^+ + e^-$</td>
<td>1.0</td>
<td>2</td>
</tr>
<tr>
<td>CR7</td>
<td>$HD + C.R. \rightarrow HD^+ + e^-$</td>
<td>2.09</td>
<td>2</td>
</tr>
<tr>
<td>CR8</td>
<td>$HD + C.R. \rightarrow H + D^+ + e^-$</td>
<td>0.04</td>
<td>2</td>
</tr>
<tr>
<td>CR9</td>
<td>$HD + C.R. \rightarrow H + D$</td>
<td>3.26</td>
<td>2</td>
</tr>
<tr>
<td>CR10</td>
<td>$D_2 + C.R. \rightarrow D_2^+ + e^-$</td>
<td>2.09</td>
<td>2</td>
</tr>
<tr>
<td>CR11</td>
<td>$D_2 + C.R. \rightarrow D + D^+ + e^-$</td>
<td>0.09</td>
<td>2</td>
</tr>
<tr>
<td>CR12</td>
<td>$LiH + C.R. \rightarrow Li + H^+$</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>CR13</td>
<td>$LiD + C.R. \rightarrow Li + D^+$</td>
<td>100</td>
<td>2</td>
</tr>
</tbody>
</table>

Notes: C.R. represents a cosmic ray. $\zeta_H$, the cosmic ray ionization rate of atomic hydrogen, is an adjustable parameter in our models.

References: 1 – Walmsley, Flower, & Pineau des Forêts (2004); 2 – assumed same as corresponding H process.

Table A14. Chemical processes: cosmic ray induced photodetachment, photodissociation and photoionization (CP) .

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>$\sigma_{X,eff,Ht}$ (Mb)</th>
<th>$\sigma_{X,eff,H}$ (Mb)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP1</td>
<td>$H^- + \gamma_{cr} \rightarrow H + e^-$</td>
<td>5.0</td>
<td>5.8</td>
<td>1</td>
</tr>
<tr>
<td>CP2</td>
<td>$D^- + \gamma_{cr} \rightarrow D + e^-$</td>
<td>5.0</td>
<td>5.8</td>
<td>2</td>
</tr>
<tr>
<td>CP3</td>
<td>$Ht^+ + \gamma_{cr} \rightarrow H + H^+$</td>
<td>5.0</td>
<td>6.6</td>
<td>3</td>
</tr>
<tr>
<td>CP4</td>
<td>$HD^+ + \gamma_{cr} \rightarrow H + D^+$</td>
<td>2.5</td>
<td>3.3</td>
<td>2</td>
</tr>
<tr>
<td>CP5</td>
<td>$HD^+ + \gamma_{cr} \rightarrow D + H^+$</td>
<td>2.5</td>
<td>3.3</td>
<td>2</td>
</tr>
<tr>
<td>CP6</td>
<td>$D_2^+ + \gamma_{cr} \rightarrow D + D^+$</td>
<td>5.0</td>
<td>6.6</td>
<td>2</td>
</tr>
<tr>
<td>CP7</td>
<td>$Li^+ + \gamma_{cr} \rightarrow Li^+ + e^-$</td>
<td>1.0</td>
<td>1.3</td>
<td>4</td>
</tr>
<tr>
<td>CP8</td>
<td>$Li^- + \gamma_{cr} \rightarrow Li + e^-$</td>
<td>1.0</td>
<td>1.0</td>
<td>5</td>
</tr>
<tr>
<td>CP9</td>
<td>$He^+ + \gamma_{cr} \rightarrow He + Hep$</td>
<td>5.0</td>
<td>5.0</td>
<td>6</td>
</tr>
<tr>
<td>CP10</td>
<td>$LiH^+ + \gamma_{cr} \rightarrow Li + H^+$</td>
<td>100</td>
<td>100</td>
<td>7</td>
</tr>
<tr>
<td>CP11</td>
<td>$LiD^+ + \gamma_{cr} \rightarrow Li + D^+$</td>
<td>100</td>
<td>100</td>
<td>2</td>
</tr>
</tbody>
</table>

Notes: $\gamma_{cr}$ represents a secondary photon, produced by cosmic-ray induced excitation of $H$ or $Ht$, as described in Section 3.3. The references listed are the sources from which we have taken our photodissociation or photoionization cross-sections. The emission probabilities $P_{Ht}(v)$ used to calculate $\sigma_{X,eff,Ht}$ are rough estimates based on the emission spectra given in Sternberg, Dalgarno, & Lepp (1987) and are likely accurate only to within a factor of a few.

References: 1 – Wishart (1979); 2 – assumed same as for corresponding H reaction; 3 – Dunn (1968); 4 – Verner & Ferland (1996); 5 – order of magnitude estimate; 6 – estimate, based on Stancil (1994); 7 – rough estimate, based on thermal rate in Galli & Palla (1998).