Hydrogen ionization in the solar atmosphere

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photosphere: 3% ionized
low chromosphere: 0.1-50%
ionized
Hα chromosphere: 10% - 99% ionized
corona: 100% ionized
Ionization is a substantial buffer of energy

Ionization strongly affects thermal evolution

H: 90% of nuclei

He: 10% of nuclei

- \( \frac{E(H \rightarrow H_2)}{E_{th}} = 22 \) @ 2 kK
- \( \frac{E(H \text{ I} \rightarrow H \text{ II})}{E_{th}} = 17 \) @ 8 kK
- \( \frac{E(He \text{ I} \rightarrow He \text{ II})}{E_{th}} = 3 \) @ 10 kK
- \( \frac{E(He \text{ II} \rightarrow He \text{ III})}{E_{th}} = 2 \) @ 30 kK
Ionization is slow in the chromosphere

rate equations:

\[
\frac{Dn_1}{Dt} = n_2 P_{21} - n_1 P_{12}
\]

\[
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\]

\[
n_H = n_1 + n_2
\]

solution:

\[
n_1(t) = n_1(\infty) + [n_1(0) - n_1(\infty)]e^{-t(P_{12} + P_{21})}
\]

\[
n_1(\infty) = \frac{n_H P_{21}}{P_{12} + P_{21}}
\]
Ionization is slow in the chromosphere

\[ n_1(t) = n_1(\infty) + [n_1(0) - n_1(\infty)]e^{-t(P_{12}+P_{21})} \]
How does hydrogen ionize?
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slow leakage between n=1 and n=2 because of 10.2 eV jump
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fast equilibration of excited states and continuum

slow leakage between n=1 and n=2 because of 10.2 eV jump
Bifrost
see Gudiksen et al., 2011, A&A, 531, 154

3D MHD code, MPI parallelized

- photospheric radiation
- thermal conduction
- non-equilibrium ionization
- etc...
How to deal with H ionization

- 9 extra variables + 8 MHD variables = 17 variables
- 7 hydrogen populations are advected

\[
\frac{\partial n_i}{\partial t} + \nabla \cdot (n_iu) = \sum_{j,j\neq i}^{n_1} n_j P_{ji} - n_i \sum_{j,j\neq i}^{n_1} P_{ij},
\]

\[
\frac{\partial n_{H2}}{\partial t} + \nabla \cdot (n_{H2}u) = R_f n_1^3 - R_b n_1 n_{H2}
\]

- \(n_e\) and \(T_g\) are not advected
- close system with energy, particle and charge conservation
How to deal with H ionization

energy conservation:

\[ F_2 = 1 - \frac{1}{e_i} \left( \frac{3kT}{2} \right) \left[ n_e + n_{\text{noH}} + n_{\text{H}_2} + \sum_{i=1}^{6} n_i \right] \]

\[ + n_{\text{H}}^{\text{tot}} e_{\text{noH}} + n_{\text{H}_2} e_{\text{H}_2} + \sum_{i=1}^{6} n_i \chi_i \right) = 0, \]
How to deal with H ionization

charge conservation:

\[ F_1 = 1 - \frac{1}{n_e} \left( n_6 + n_{H}^{\text{tot}} n_{e}^{\text{noH}} \right) = 0. \]

pressure follows:

\[ P = kT \left( n_e + n_{H2} + \sum_{i=1}^{n_1} n_i + n_0 \right), \]

H ionization acts as an equation-of-state.
Radiation field

- detailed evaluation of radiation field $J_{\nu}$ computationally expensive
- but needed for rate equations:
  \[ P_{ij} = C_{ij}(n_e, T_e) + R_{ij}(J_{\nu}, n_e) \]
- Sollum (1999): fixed radiative rates can be used as confirmed in detailed 1D simulations
- specify $T_{\text{rad}}$ in each transition
- rate coefficients are local

\[ P_{ij} = C_{ij}(T_e, n_e) + R_{ij}(T_{\text{rad}}, n_e) \]
Lyα is special
see Carlsson & Leenaarts, 2012, A&A

- Use detailed computations to compute the Lyα downward rate:
  \[ R_{21} = L(T) \, E(\tau) \, n_e \, n_1 \]
- Solve the transfer equation using rate and \( n_1 \) populations to provide source function and (fudged, poor man’s scattering) opacity
- Obtain upward rate from \( J \)
- Rates not implicit, possible source of problems
Lya is special
Increased temperature fluctuations

HION

LTE
Unrealistic clustering at temperatures where He ionizes
No such clustering for hydrogen
H$_2$ molecules provide lower limit in LTE
Low temperature end

Time-dependent chemistry removes lower limit below $\rho = 10^{-9}$
Conclusions (1)
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- clumping of gas at 10 kK and 30kK is an artifact of LTE Helium ionization
  - real temperature structure in upper chromosphere unknown, He ionization should be modeled better
- time-dependent H$_2$ chemistry removes lower limit of temperature in expansion bubbles
Conclusions (2)

- Conclusions (1) are generally valid
- Magnetized chromosphere influenced by ionization-dependence of neutral-ion effects
- See Juan’s (and others) talk for details