HyRec-2

A code for primordial hydrogen and helium recombination including radiative transfer

Version: July 2020

By Yacine Ali-Haïmoud and Chris Hirata (2010-17)

with contributions from Nanoom Lee (2020)

0.1 Contents of the package

0.1.1 Source code files

`hyrectools.c, hyrectools.h`: array creation and interpolation routines.

`helium.c, helium.h`: helium recombination routines.

`hydrogen.c, hydrogen.h`: hydrogen recombination routines. New default mode (SWIFT) is added in HYREC-2.

`history.c, history.h`: integration routines.

`energy_injection.c, energy_injection.h`: energy injection routines (DM annihilation, PBH, etc). Any other general energy injections can be added easily.

`hyrec.c`: main recombination program.

0.1.2 Data files

`fit_swift.dat`: table of correction function Δ and its first derivatives w.r.t $\hat{\omega}_{cb} \equiv \omega_{cb}(T_0^{\rm FIRAS}/T_0)^3$, $\hat{\omega}_{\rm H} \equiv \omega_b(1-Y_{\rm He})(T_0^{\rm FIRAS}/T_0)^3$, $N_{\rm eff}$ as a function of radiation temperature at fiducial cosmology.
Columns are:
T_r, $\Delta(T_r)$, $\frac{\partial\Delta}{\partial\hat{\omega}_{cb}}$, $\frac{\partial\Delta}{\partial\hat{\omega}_H}$, and $\frac{\partial\Delta}{\partial N_{\rm eff}}$.

`Alpha_inf.dat`: table of effective recombination coefficients for hydrogen.
$\mathcal{A}_{2s}(T_m, T_r)$ and $\mathcal{A}_{2p}(T_m, T_r)$ (in $\rm cm^3 s^{-1}$) for $0.004 \leq T_r \leq 0.4$eV and $0.1 \leq T_m/T_r \leq 1$.

`R_inf.dat`: table of effective 2p $\rightarrow$ 2s transfer rate for hydrogen.
$\mathcal{R}_{2p,2s}(T_r)$ (in $\rm s^{-1}$) for $0.004 \leq T_r \leq 0.4$eV.
[Effective rates are extrapolated to an infinite number of excited states of hydrogen, $n_{\rm max} \rightarrow \infty$.]

`two_photon_tables.dat`: table of two-photon transition rates. Columns are:
E_b (in eV), $3A_{2p,1s}\phi_{\rm Ly\alpha}(\nu)\Delta\nu_b$ (in $\rm s^{-1}$), $d\Lambda_{2s,1s}/d\nu\Delta\nu_b$ (in $\rm s^{-1}$), $(d\Lambda_{3s,1s}/d\nu + 5d\Lambda_{3d,1s}/d\nu)\Delta\nu_b$ (in $\rm s^{-1}$), $(d\Lambda_{4d,1s}/d\nu + 5d\Lambda_{4d,1s}/d\nu)\Delta\nu_b$ (in $\rm s^{-1}$).

`input.dat`: example input file for cosmological parameters. See the comments in the file for the explanation of each parameter.

0.2 How to run HYREC-2

0.2.1 Compiling the code

Open a terminal session, enter the HyRec folder, and type at the command line, if gcc is your C compiler (-O3 is an optimizing option, it makes the code run a little faster):

```
gcc -lm -O3 hyrectools.c helium.c hydrogen.c history.c energy_injection.c hyrec.c -o hyrec
```

0.2.2 Computing a recombination history

Once you have compiled the code, simply type at the command line:

```
./hyrec < input.dat
```

The code will compute the recombination history and print three columns or seven columns in `output_xe.dat` depending on the flag for recombination spectrum related quantities (`PRINT_SPEC` in `history.h`). The first three columns are always:
z, x_e, and T_m (in eV).

0.3 Reference

If you use HYREC-2, please cite the companion papers:

N. Lee & Y. Ali-Haimoud — (2020)
Y. Ali-Haimoud & C. M. Hirata, 2010, Phys. Rev. D 83, 043513 (2011)

You may also refer to the following papers, on which this work relies substantially:

Y. Ali-Haimoud & C. M. Hirata, Phys. Rev. D 82, 063521 (2010)
C. M. Hirata, Phys. Rev. D 78, 023001 (2008)
E. R. Switzer & C. M. Hirata, Phys. Rev. D 77, 083008 (2008)

0.4 Switchs

HYREC-2 computes by default what we believe is the most accurate and fast recombination history. If you would like to see yourself what the difference is with previous physical models, or what impact various new effects have on recombination, we have left some switches to play with (for hydrogen recombination only):

In history.h, you can choose to use the fastest and accurate full recombination calculation (which is the default), in which case leave the following line unchanged: `#define MODEL SWIFT`
You can choose to use the full recombination calculation (which was the default of HYREC), in which case you should change the above line to: `#define MODEL FULL`
You can also choose to use Peebles' effective three-level atom model, in which case you should change the above line to: `#define MODEL PEEBLES`
or an effective three-level atom model for hydrogen with a fudge factor F = 1.14, similar to the first version of RECFAST, in which case change the line to: `#define MODEL RECFAST`
You can also use the correct effective four-level atom model, but with Lyα only (treated in the Sobolev approximation) and 2s–1s two-photon decays (treated with a simple total decay rate), no feedback or other radiative transfer effects, with: `#define MODEL EMLA2s2p`

When using the FULL calculation, you can, if you wish, switch on and off two-photon processes and diffusion. Various switches are available in hydrogen.h. By default, all switches should be on (value = 1). You can switch them off (value = 0) if you wish. All switches set to zero corresponds to an effective four-level atom model with Lyα, Lyβ and Lyγ treated in the Sobolev approximation

and feedback between them. The available switches are EFFECT_A (correct handling of 2s–1s decays and absorptions, both in the radiative transfer and to compute the total 2s–1s decay rate), EFFECT_B (sub-Lyα two- photon transitions), EFFECT_C (super-Lyα two-photon transitions), EFFECT_D (Raman scattering), and DIFFUSION (frequency diffusion in Lyα).

0.5 Varying the fine-structure constant and the electron mass

The user can now easily input a different fine-structure constant or electron mass at recombination than today's value (they are however assumed to be constant during recombination). This can be done by providing α(rec)/α(today) and me(rec)/me(today) as input parameters in `input.dat`.

0.6 Revision history

For the detailed revision history, check the preamble of each code.

The code is available in https://github.com/nanoomlee/HYREC-2
Last updated July 2020.