HyRec

A code for primordial hydrogen and helium recombination including radiative transfer

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Contents of the package:

Source code files:

`hyrectools.c, hyrectools.h`: array creation and interpolation routines (previously `arrays.c/h`)

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

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

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

`hyrec.c, hyrec_params.h`: main recombination program and accuracy parameters

Data files:

`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 $cm^3 s^{-1}$) 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 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, $n_{max} \rightarrow \infty$]

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

`input.dat:` example input file for cosmological parameters (see below for a description)

Using HyRec:

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 hyrec.c -o hyrec
```

Computing a recombination history:

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

```
./hyrec
```

You will be prompted to enter the value of the following cosmological parameters:
$\boldsymbol{T_0}$ [CMB temperature today, in Kelvin], $\boldsymbol{\Omega_b h^2}$ [baryon density], $\boldsymbol{\Omega_m h^2}$ [total matter density, CDM+ baryons], $\boldsymbol{\Omega_k h^2}$ [curvature density], $\boldsymbol{\Omega_\Lambda h^2}$ [dark energy density], $\boldsymbol{w_0}$, $\boldsymbol{w_a}$ [parameters of the dark energy equation of state, $w(a) = w_0 + w_a(1 - a)$], $\boldsymbol{N_{\nu,\mathrm{eff}}}$ [effective number of neutrino species]. The fine-structure constant and electron mass can also be entered as inputs (see below).

Once you have entered all required parameters, the code will compute the recombination history and print three columns to the screen: redshift z from 8000 down to 0, spaced by $\Delta z = 1$, free electron fraction x_e, and ratio of matter to radiation temperature $T_\mathrm{m}/T_\mathrm{r}$.

Using input and output files:

If you do not want a prompt to appear every time you run the code, you can switch it off by setting, at the beginning of `hyrec_params.h`: `#define PROMPT 0`
You can enter your input cosmological parameters into a file, in the order written above.
If your input file is named `input.dat` (see example provided in the package), and you wish the recombination history to be printed out to the output file `output.dat` instead of the screen, type at the command line:

```
./hyrec < input.dat > output.dat
```

If you use HyRec, please cite the companion paper:

Y. Ali-Haïmoud & 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-Haïmoud & 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)

Switches

HyRec computes by default what we believe is the most accurate 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 `hyrec_params.h`, you can choose to use the full recombination calculation (which is the default), in which case leave the following line unchanged: `#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).

Printing out the Lyman-lines distortion:

It is now possible to print out the Lyman distortion (from half the Lyα frequency to the Lyγ frequency; not including distortion photons from helium recombination). To do so, use the switch `#define PRINT_SPEC` in `hyrec_params.h` , and modify the desired redshifts if necessary. It is recommended to use the higher accuracy tables and integration parameters in `hyrec_params.h` to obtain a smoother spectrum.

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 uncommenting the appropriate paragraph in `history.c` (line 100) and providing $\alpha(\mathrm{rec})/\alpha(\mathrm{today})$ and $m_e(\mathrm{rec})/m_e(\mathrm{today})$ as input parameters, either at the command line or in an input file.

Revision history

- **First release: November 2010.**

- **Second release: January 2011**

- Numerical integration switches from post-Saha expansions to explicit ODE integration were changed. The code is now well behaved for a wide range of cosmologies (in the previous version, numerical instabilities appeared at high redshift for some cosmologies). For more details, see Secs. V E (for hydrogen) and VI B (for helium) in the companion paper.

- The range of temperatures for the tabulated effective rates was extended to allow computations of the recombination history down to $z = 20$ (instead of 200 in the previous version). The used effective rates were extrapolated from rates computed with n_{max} up to 600 (vs. 500 in the previous version) in order to reach sufficient accuracy even at low temperatures.

- The differential two-photon decay rate from 2s, $d\Lambda_{2s,1s}/d\nu$ is now automatically normalized to the total 2s--1s decay rate $\Lambda_{2s,1s}$, the value of which can be set by the user with the constant `L2s1s` in `hydrogen.h`.

- **Third release: May 2012 (this version)**

- File names were changed (`arrays.c` renamed `hyrectools.c`) and some of the contents of `hyrec.c` were transferred to `history.c`, for ease of inclusion into a Boltzmann code.
- The post-Saha expansion was made more accurate.
- The numerical solution of radiative transfer was made more robust by analytically subtracting nearly canceling terms, and computing departures from thermal equilibrium. The Lyman-lines spectrum can now be easily extracted.
- The integration is extended down to $z = 0$ with Peebles' model once $T_r < 0.004$ eV (corresponding to $z \simeq 15$).
- The explicit dependences on the fine-structure constant and electron mass are now included.
- For more details, refer to the technical explanatory supplement and the comments in the source files.

This code is provided "as is" and no guarantees are given regarding its accuracy.
For questions or issues, please email *yacine@ias.edu*

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