Analysis tools for the RADYN M-dwarf flare model grid

Explanation of the contents and use of the Zenodo repository
"The data for Time-dependent Stellar Flare Models of Deep Atmospheric Heating"

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Contents

1 Introduction

This manual contains information about the output files from the public M-dwarf RADYN flare model grid (v1.0), which is described in Kowalski, Allred, & Carlsson 2024 (submitted to *AAS* journals on Feb 12, 2024; hereafter, KAC24). This manual supplements the information that is already in `analysis_tools.pdf` and `radyn_manual.pdf` which are available through the link (https://folk.universitetetioslo.no/matsc/radyn/) that is provided in the F-CHROMA solar flare model grid paper (Carlsson et al. 2023). We refer users to the IDL routines that are linked there for more information as well. Because a large and sophisticated suite of IDL routines is necessary to calculate contribution functions from the RADYN output, we have done this on our end and have provided the output in `.fits` tables to be read into any computer language.

If you make use of the M-dwarf RADYN model flare grid, please cite the main model paper (KAC24; **DOI: TBD**) and the Zenodo repository DOI (below), in addition to Carlsson & Stein (1992), Carlsson & Stein (1995), Carlsson & Stein (1997), and Allred et al. (2015). If you make use of the hydrogen emission line spectra from the grid, please additionally cite Tremblay & Bergeron (2009) for the TB09+HM88 opacity line profile calculations and Kowalski et al. (2022) for the description of how they were incorporated into the RADYN source code.

2 Installation & Download

The `.fits` files are distributed from the CERN Data Centre's Zenodo repository. To read the `.fits` files into Python (3.11), we have created a Jupyter notebook (`radyn_xtools_Demo.ipynb`), which can be downloaded from the Zenodo repository link as well. The Python tools (`radyn_xtools`) that are used in this notebook can be installed through the following commands. For more information, please see the Python Packaging Index (PyPI) webpage for the `radyn_xtools` software at: www.pypi.org/project/radyn-xtools/

1. A new conda environment is recommended (it is assumed that the user has Anaconda installed):

   ```
   conda create --name your_new_env python=3.11
   ```

2. Install routines through the Python Package Index (PyPI):

   ```
   conda activate your_new_env
   pip install radyn_xtools
   ```

   This will install the analysis routines and the dependencies.

3. Download the `grid-v1.0.tar.gz` file (4.1 GB) containing the `.fits` files and the Jupyter notebook at the Zenodo repository "The data for Time-dependent Stellar Flare Models of Deep Atmospheric Heating" (10.5281/zenodo.10929515). Unpack where you want to permanently store the grid files on your system:

   ```
   tar -xzvf grid-v1.0.tar.gz
   ```

   will unpack the files and sub-directories. One should keep the file locations and sub-directory structure intact.

   Follow instructions in the Jupyter notebook.

   If emission line contribution functions other than hydrogen Balmer γ are needed, a file called

   `linecontribfunct-other-v1.0.tar.gz` can be optionally downloaded (9.2 GB) from Zenodo and unpacked within the same base directory as the rest of the grid files.

   The total size of all unpacked files is about 28 GB.

3 Description of the FITS files

Units are in the centimeter-gram-seconds (*cgs*) system, except wavelengths are in units of Å. The atmospheric depth (interface) index, `k`, runs from `k = 0` (at the loop apex) to `k = 249 = ndepth - 1` (at bottom of the atmosphere in the deep photosphere). Note that the height value at a given grid interface index changes over time due to the adaptive grid. Most arrays have `ntime = 50` temporal points, given by index `t`, (e.g., $t = 0 - 9.8$ s at

$\Delta t = 0.2$ s intervals). However, some models are extended for longer, some until $t = 5$ s, and some do not have precisely 0.2 s intervals, so the user should be aware (see Jupyter notebook).

`radyn_out.<model_id>.fits`

- stores the atmospheric thermodynamic and hydrodynamic variables that vary with time (and some other salient data about the atomic physics for each element in detail).

`timet`	`[t]`	time (s)
`z1t`	`[k, t]`	height at interfaces: arc distance (cm) above $\tau_{5000}(t = 0\text{s}) = 1$
`cmass1t`	`[k, t]`	column mass densities (g cm^{-2}) at interfaces
`tg1t`	`[k, t]`	gas, or plasma, temperature (K)
`pg1t`	`[k, t]`	gas, or plasma, pressure (dyn cm^{-2})
`n1t`	`[k, i, iel, t]`	population densities (cm^{-3}) for H I/II, Ca II, He I/II/III
`ne1t`	`[k, t]`	ambient (thermal) electron density (cm^{-3})
`d1t`	`[k, t]`	gas, or plasma, mass density (g cm^{-3})
`vz1t`	`[k, t]`	macroscopic gas, or plasma, velocity (cm s^{-1}); positive is upflow
`bheat1t`	`[k, t]`	nonthermal electron beam heating (erg cm^{-3} s^{-1})
`f20t`	`[t]`	injected energy flux density of beam (erg cm^{-2} s^{-1})
`hnt_ct`	`[k, ij, t]`	nonthermal collisional excitation rate (s^{-1} per H atom in lower state)
`xheat1t`	`[k, t]`	XEUV backheating rate (erg cm^{-3} s^{-1})
`tdheat1t`	`[k, t]`	prescribed coronal heating rate (erg cm^{-3} s^{-1})
`trl1t`	`[k, t]`	optically thin radiative cooling rate (erg cm^{-3} s^{-1})
`coolt`	`[k, kr, t]`	net detailed radiative heating or cooling rate (erg cm^{-3} s^{-1}) over wavelengths of transition `kr`
...	...	...
...	...	...

  The rest of the variables are explained in `analysis_tools.pdf`, which is distributed with the F-CHROMA grid of solar flare models. Here, τ_{5000} is the optical depth at $\lambda = 5000$ Å. Note that the electron density, `ne1t`, does not include the electrons in the beam. The non-equilibrium population densities of the elements treated in detail are given by `n1t`, where `iel = 0` is the element number for H I/II, 1 for Ca II/III, and 2 for He I/II/III; level `i = 0` corresponds to the ground state level of the respective ion or atom, `i = 5` corresponds to $n_p = n_{\rm H\,II}$ for `iel=0`, and `i = 8` corresponds to $n_{\rm He\,III}$ for `iel=2`. The `hnt_ct` is the nonthermal collision excitation or ionization rate of hydrogen: `ij = 0` corresponds to principal quantum number `n = 1` to continuum, `ij = 1` corresponds to `n = 1` $\rightarrow$ `n = 2`, `ij = 2` corresponds to `n = 1` $\rightarrow$ `n = 3`, and `ij = 3` corresponds to `n = 1` $\rightarrow$ `n = 4`.

- `radyn_xtools.load_atmos(model_id = '<model_id>')` is recommended for reading in the `.fits` files (see Jupyter notebook).

`spectra/spec.<model_id>.fits`

- Contains spectra at the 95 continuum wavelengths that are calculated in detail and spectra over the three hydrogen Balmer lines that are calculated in detail. There are three extensions to each file. The first extension stores the spectra as a function of time; the second extension stores the time-averaged spectra; the third extension stores the hydrogen Balmer γ spectra (as a function of time and time-averaged) that are interpolated to $n\lambda = 327$ wavelength points. All spectra are radiative surface flux density (erg cm^{-2} s^{-1} Å^{-1}), but the continuum and the $n\lambda = 327$ point Hγ intensity spectra (erg cm^{-2} s^{-1} Å^{-1} sr^{-1}) at five μ values $(0.05, 0.23, 0.50, 0.77, 0.95)$ are included as well. The fields `Flam` and `Flam_prime` refer to F_λ and F'_λ, respectively.

- `radyn_xtools.load_spec()` is recommended for reading in the `.fits` files (see Jupyter notebook). Specific times are read in by setting the `time` parameter, while `time = -9` reads in the time-averaged spectrum and `time = -99` reads in spectra at all times in the model. The parameter `stype` determines what is read

into memory: `stype = 'cont_flx'` is the radiative surface flux, `stype = 'cont_i95'` is the emergent continuum intensity at $\mu = 0.95$, `stype = 'Hg_flx'` is the radiative surface flux of the Balmer Hγ line at 31 wavelength points, and `stype = 'Hg_flx_VCS'` is the radiative surface flux of the Balmer Hγ line with a fine $n\lambda = 327$-point interpolation (more options are given in the Jupyter notebook). We recommend considering both calculations of the hydrogen Balmer γ profiles in your analyses.

– `radyn_xtools.load_contlc()` loads a light curve at a specified (`wave`) continuum wavelength. The parameter `stype` can be `'cont_flx', 'cont_i95', 'cont_i77', 'cont_i50', 'cont_i23', 'cont_i05'`. A dictionary is returned, and a radiation (brightness) temperature can be optionally returned in the dictionary (see Jupyter notebook).

`ccontribf/ccontribf.<model_id>.fits`

– Contribution function to the emergent intensity ($\mu = 0.95$) at continuum wavelengths calculated in detail. The contribution functions and optical depths are provided at the 53 selected wavelengths over the range of $\lambda = 700 - 20,900$ Å that are shown in the bottom panel of Figure 8 in KAC24.

`cim_t`	`[wl, k, t]`	contribution function to emergent intensity at $\mu = 0.95$ (erg cm^{-2} s^{-1} Å^{-1} sr^{-1} per unit log$_{10}$ column mass)
`ciz_t`	`[wl, k, t]`	contribution function to emergent intensity at $\mu = 0.95$ (erg cm^{-2} s^{-1} Å^{-1} sr^{-1} cm^{-1})
`cip_t`	`[wl, k, t]`	cumulative contribution function, from 0.0 at `k = 0` to 1.0 at `k = 249`
`mci_t`	`[wl, k, t]`	column mass (g cm^{-2})
`zci_t`	`[wl, k, t]`	height (cm)
`tau_ci_t`	`[wl, k, t]`	wavelength-dependent optical depth at $\mu = 0.95$
`citime`	`[t]`	time (s)
`wl_ci`	`[wl]`	vacuum wavelength (Å)

– `radyn_xtools.load_contci()` is recommended for reading in the `.fits` files (see Jupyter notebook).

`lcontribf/lcontribf.<model_id>.fits`

– Contribution function to the emergent intensity ($\mu = 0.95$) over the wavelengths of the following optical and near-infrared bound-bound transitions that are calculated in detail:

  – hydrogen Balmer α ($\lambda_{0,\mathrm{vac}} = 6564.77$ Å)
  – hydrogen Balmer β ($\lambda_{0,\mathrm{vac}} = 4862.86$ Å)
  – hydrogen Balmer γ ($\lambda_{0,\mathrm{vac}} = 4341.84$ Å)
  – hydrogen Paschen α ($\lambda_{0,\mathrm{vac}} = 18757.41$ Å)
  – hydrogen Paschen β ($\lambda_{0,\mathrm{vac}} = 12822.38$ Å)
  – calcium II K ($\lambda_{0,\mathrm{vac}} = 3934.77$ Å)
  – calcium II H ($\lambda_{0,\mathrm{vac}} = 3969.59$ Å)
  – calcium II ($\lambda_{0,\mathrm{vac}} = 8544.41$ Å)
  – helium I ($\lambda_{0,\mathrm{vac}} = 10833.26$ Å)

  The source function, opacity, and optical depth ($\mu = 0.95$) arrays are stored for each line. The contribution functions for all lines except for hydrogen Balmer γ are obtained from the supplemental file:

  `linecontribfunct-other-v1.0.tar.gz`

– `radyn_xtools.ci_image1()` is recommended for reading in the `.fits` files and displaying emission line contribution functions (see Jupyter notebook).

`modelvals/modelvals.tave.fits`

- Stores all of the quantities, including those in Table 2 of KAC24, calculated from the temporally averaged, flare-only spectra F'_λ (with `p` below indicating that the quantity was calculated from the flare-only spectrum or the pre-flare value was subtracted). The fields are the following:

`field`	Description
`model_id`	model identification (col 1 of Table 2)
`group`	model group (`main, const, Ec37, sol, thermal, auxiliary, N+20`) in Table 2
`Fnum`	F# (e.g., F13); energy flux density of injected electron beam
`Ec_keV`	low-energy cutoff (keV) of injected electron beam
`C4170p_ave`	C4170′ (col 2 of Table 2)
`C3615p_ave`	C3615′ (combined with `C4170p_ave` for col 8 of Table 2)
`Hgp_ave`	line-integrated flux of hydrogen Balmer γ (col 3 of Table 2)
`Hgp_C4170p_ave`	Line-to-continuum ratio (col 4 of Table 2)
`Hgp_eff_width`	Effective width of hydrogen Balmer γ (col 9 of Table 2)
`Hgp_FWHM`	FWHM of hydrogen Balmer γ
`Tbbp_ave`	the temperature, $T_{\rm BB}$, of a blackbody fit (col 7 of Table 2)
`TFcolorRp_ave`	the temperature, $T_{\rm FcolorR}$, of a blackbody fit
`FcolBp_ave`	the flux ratio FcolorB
`FcolRp_ave`	the flux ratio FcolorR

- `radyn_xtools.load_modelvals_ave()` is recommended for reading in these calculated quantities (`field` value) from the `.fits` file above (see Jupyter notebook).

`modelvals/modelvals.<model_id>.dat`

- An `ascii` file for each model with calculated quantities from the flare-only spectra $F'_\lambda(t)$ as a function of time.
- `radyn_xtools.load_modelvals_t()` is recommended for reading in the following calculated quantities as a function of time: `Tbbp` (col 5 and col 6 of Table 2 of KAC24) and `TFcolorRp`.

`RH_input/rhinput.<model_id>.atmos`

- An `ascii` file at every time-step in every model with column mass, temperature, electron density, gas velocity (negative corresponds to downward), the default microturbulence parameter, and non-equilibrium population densities of hydrogen. The format is the standard format for input atmospheric files that are used by the `RH` radiative transfer code (Uitenbroek 2001). One should note that adjustments to the H I populations were made to the values in these files (because `RH` automatically reduces H I populations due to H_2, and this is already accounted for in `n1t` arrays from `RADYN`.).
- `radyn_xtools.read_rh()` reads the `ascii` files into a dictionary (see Jupyter notebook).

`run/`

- The `run/` directory includes sample input files, such as the atomic data, the `opac/` directory, the starting atmosphere, etc ... These files may be of interest to experienced `RADYN` users.

  The `fortran` source code (`prog/` directory) that was used to produce the grid of models is not included in this distribution. We refer the interested user to the source code distributed with the F-CHROMA project.

4 Description of the unique model identifications

Each model as a unique identifier, `model_id`.

For example, `mF13-85-3` corresponds to the model with a ramping injected beam flux to a maximum beam flux density of 10^{13} erg cm^{-2} s^{-1} (F13), a low-energy cutoff of $E_c = 85$ keV, and a number flux density power-law index of $\delta = 3$ at $E > E_c$. Whereas, `cF13-85-3` has a constant injected beam flux density of 10^{13} erg cm^{-2} s^{-1} from $t = 0 - 2.3$ s, and the "c" models are calculated up to $t = 5$ s. If the beam injection duration (for "c" models) or timescale (for "m" models) is not 2.3 s, it is indicated first in the model identification. For example, `c15s-5F11-25-4` corresponds to a $\Delta t = 15$ s injected beam energy flux density of 5×10^{11} erg cm^{-2} s^{-1} above a low-energy cutoff of 25 keV with a power-law index of $\delta = 4$.

References

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