Starmatrix Documentation

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USER GUIDE:

Modelling nucleosynthesis of galactic chemical elements

Starmatrix is a Q-Matrix generator.

Based on explicit values for *solar abundances*, *Z* and *IMF*, Starmatrix calculates matrices `Q(i,j)` of masses of elements `i` ejected to the galactic medium as element `j`, for a complete range of stellar masses, accounting for supernovae of types *I* and *II*.

A technique based on the *Q-matrix formalism* (*Talbot & Arnett, 1973*; *Ferrini et al., 1992*; *Portinari et al., 1998*) is used to calculate the elemental abundances.

Starmatrix computes the contribution matrix of 15 elements:

H	D	He3	He4	C	C13	N	O	Ne	Mg	Si	S	Ca	Fe

and neutron rich isotopes (referred as `n.r.` in the code).

Codebase

The code for *Starmatrix* is hosted at GitHub under a MIT license.

CHAPTER

ONE

INSTALLATION

The easiest way to install the package is using pip:

```
$ pip install starmatrix
```

This will also install some dependencies if they are not found in the system: **numpy**, **scipy** and **pyyaml**

1.1 Updating

A previous installation can be upgraded to the latest version with:

```
$ pip install --upgrade starmatrix
```

1.2 Uninstall

To remove Starmatrix from your system run:

```
$ pip uninstall starmatrix
```

CHAPTER

TWO

USAGE

2.1 Basic

Use Starmatrix running:

```
$ starmatrix --config FILENAME
```

where *FILENAME* is the path to the config yaml file.

Running Starmatrix will produce a directory with three output files:

- **mass_intervals**: all the mass intervals used to integrate for all the mass range
- **imf_supernova_rates**: the initial mass functions for the supernova rates for each mass interval
- **qm-matrices**: the Q(m) matrices for every mass interval defined in the *mass_intervals* file

2.2 Advanced

If you have Starmatrix installed in your system, you can import its modules, classes and functions to use them in your own code.

2.2.1 Module List

This is the list of all Starmatrix modules:

```
starmatrix.abundances
starmatrix.constants
starmatrix.dtds
starmatrix.elements
starmatrix.supernovae
starmatrix.functions
starmatrix.imfs
starmatrix.matrix
starmatrix.model
starmatrix.settings
```

starmatrix.abundances

This modules include chemical abundances data: solar abundances from different papers/authors and the Abundances class, that can be subclassed to define new abundances datasets.

starmatrix.abundances code at GitHub

starmatrix.constants

This modules defines constants to use internally or as default parameters if left empty by the user.

starmatrix.constants code at GitHub

starmatrix.dtds

The dtds module contains some predefined Delay Time Distributions from different papers/authors.

starmatrix.dtds code at GitHub

starmatrix.elements

This module includes the Expelled class, used to read the file containing ejected elements data and use it to interpolate for any given mass.

starmatrix.elements code at GitHub

starmatrix.supernovae

The supernovae module contains several datasets of Supernova ejections for different metallicities.

starmatrix.supernovae code at GitHub

starmatrix.functions

A module grouping utility methods used all around by Starmatrix modules like functions for converting between stellar mass and stellar lifetimes or to integrate initial mass functions.

starmatrix.functions code at GitHub

starmatrix.imfs

This module contains some predefined Initial Mass Functions from different papers/authors and the IMF class, that can be subclassed to define new initial mass functions.

starmatrix.imfs code at GitHub

starmatrix.matrix

This module contains functions to compute Q-matrices of elements for a given mass, and Q-matrices of elements coming from Supernova events.

starmatrix.matrix code at GitHub

starmatrix.model

The Model class is the one actually running the explosive nucleosynthesis for the configured stellar mass range and writing the Q-matrices and the other output files.

starmatrix.model code at GitHub

starmatrix.settings

This module groups the functions in charge of defining default settings and checking all values in a set of parameters are valid. Deprecation warnings are also defined in the settings module.

starmatrix.settings code at GitHub

2.2.2 Examples

Run a model with your own custom parameters (in this example custom_params is a dict object initialized with all the default settings using the **settings.default_settings()** function, we can then modify any of the available *configuration parameters*) from inside your programs:

```
import starmatrix
import starmatrix.settings as settings
from starmatrix.model import Model

custom_params = settings.default_settings()
custom_params['binary_fraction'] = 0.13
custom_params['sol_ab'] = 'he10'
custom_params['dtd_sn'] = 'chen'

context = settings.validate(custom_params)
Model(context).run()
```

Call Starmatrix utility functions:

```
import starmatrix.functions as functions

stellar_mass = 4.3
z = 0.02
stellar_tau = functions.stellar_lifetime(stellar_mass, z)
```

Compute the contributions matrix of supernovae for a given mass:

```
import starmatrix.matrix as matrix

stellar_mass = 4.3
contribution_matrix = matrix.q_sn(stellar_mass)
```

CHAPTER

THREE

CONFIGURATION

Starmatrix reads a configuration file where several input parameters (all of them optional) can be set in yaml format:

```
z                 # Metallicity. Default value: 0.02
sol_ab            # Solar abundances data. Default value: as09
imf               # Initial Mass function to use. Default value: kroupa
imf_alpha         # If IMF is salpeter/starburst, this extra param is needed. Defaults␣
↪to 2.35
imf_m_low         # Lower limit (in solar masses) for the IMF. Default value: 0.15
imf_m_up          # Upper limit (in solar masses) for the IMF. Default value: 100
m_min             # Minimum mass (in solar masses) for the resulting Q-Matrices.␣
↪Default: 0.98
m_max             # Maximum mass (in solar masses) for the resulting Q-Matrices.␣
↪Default: 40.0
total_time_steps  # Total time steps for integration. Default value: 300
binary_fraction   # Fraction of binary systems. Default value: 0.15
dtd_sn            # Delay time distribution to use for Supernovae. Default value: rpl
sn_yields         # Dataset for Supernovae yields. Default value: iwa1998
output_dir        # Name of the directory where results are written. Defaults to "results
↪"
matrix_headers    # Flag to include headers in the qm-matrices file. Default value: yes
return_fractions  # Flag to calculate R: fraction of mass restored to the ISM. Default:␣
↪False
integration_step  # The integration step can be constant in t or in log(t). Default:
↪"logt"
dtd_correction_factor # Correction for the uncertainty in the DTD integral. Default: 1.0
deprecation_warnings  # If False Starmatrix won't show deprecation warnings. Default: True
expelled_elements_filename  # Filename of ejected data. Defaults to an internal file with
                            # data for z=0.02 from Gavilan et al, 2006, A&A, 450, 509
                            # and Chieffi & Limongi, 2004, ApJ, 608, 405
yield_corrections # A map of individual correction factors for items in the ejected data␣
↪file
```

Starmatrix will use its internal *default values* for all params for which no values are provided.

If you want to use an existent configuration file as template for your own, you can run:

```
$ starmatrix --generate-config
```

That command will create a `config-example.yml` file in the current dir.

Starmatrix uses solar mass (M*) as the reference unit for all quantities, so internally the upper and lower limits for IMF are expressed in solar masses, Delay Time Distributions are expressed as [Supernovae per Year per M*] and the

expelled elements file is expected to express data as expelled mass per solar mass, same as the supernova yields.

3.1 Initial mass function

The `imf` param in the config file can be set to use any of the predefined IMFs from different papers/authors:

salpeter
Salpeter 1955

starburst
Starburst 1999 (a Salpeter with mass limits in [1, 120])

miller_scalo
Miller & Scalo 1979

ferrini
Ferrini, Palla & Penco 1998

kroupa2001
Kroupa 2001

kroupa2002
Kroupa 2002

chabrier
Chabrier 2003

maschberger
Maschberger 2012

The default value is `kroupa2002`. If you want to use your own IMF you can do so subclassing the IMF class.

The IMF will be normalized integrating in the `[imf_m_low, imf_m_up]` mass interval (default: `[0.15, 100]`, except `Starburst`: `[1, 120]`).

3.2 Solar abundances

The `sol_ab` param in the config file can be set to use any of the available abundances datasets from different papers/authors:

ag89
Anders & Grevesse 1989

gs98
Grevesse & Sauval 1998

as05
Asplund et al. 2005

as09
Asplund et al. 2009

he10
Heger 2010

lo19
Lodders et al. 2019

The default value is `as09`. If you want to use your own abundances data you can do so subclassing the Abundances class.

3.3 Delay Time Distributions

The `dtd_sn` param in the config file can be set to use any of the available Delay Time Distributions for supernova rates from different papers/authors:

rlp
Supernova rates from Ruiz-Lapuente et al. 2000

maoz
The DTD of Type Ia supernovae from Maoz & Graur (2017)

castrillo
DTD of Type Ia supernovae from Castrillo et al. (2021)

greggio
DTD of Type Ia supernovae from Greggio, L. (2005)

chen
DTD of Type Ia supernovae from Chen et al. (2021)

greggio-CDD04
DTD from model Close DD 0.4 Gyrs from Greggio, L. (2005)

greggio-CDD1
DTD from model Close DD 1 Gyr from Greggio, L. (2005)

greggio-WDD04
DTD from model Wide DD 0.4 Gyrs from Greggio, L. (2005)

greggio-WDD1
DTD from model Wide DD 1 Gyr from Greggio, L. (2005)

greggio-SDCH
DTD from model SD Chandra from Greggio, L. (2005)

greggio-SDSCH
DTD from model SD sub-Chandra from Greggio, L. (2005)

strolger-fit1
Phi function from Strolger et al (2020) with (, ,) = (10, 600, 220)

strolger-fit2
Phi function from Strolger et al (2020) with (, ,) = (110, 1000, 2)

strolger-fit3
Phi function from Strolger et al (2020) with (, ,) = (350, 1200, 20)

strolger-fit4
Phi function from Strolger et al (2020) with (, ,) = (6000, 6000, -2)

strolger-fit5
Phi function from Strolger et al (2020) with (, ,) = (-650, 2200, 1100)

strolger-optimized
Phi function from Strolger et al (2020) with (, ,) = (-1518, 51, 50)

3.4 Supernovae yields

The `sn_yields` param in the config file can be set to use any of the available supernova yields datasets from different papers/authors:

iwa1998
Data from Iwamoto, K. et al., 1999, ApJ 125, 439

sei2013
Data from Seitenzahl et al. 2013, MNRAS 429, 2, 1156–1172

ln2018-1
Data from Leung & Nomoto 2018, ApJ, Vol 861, 2, Id 143, Tables 6/7

ln2018-2
Data from Leung & Nomoto 2018, ApJ, Vol 861, 2, Id 143, Tables 8/9

ln2018-3
Data from Leung & Nomoto 2018, ApJ, Vol 861, 2, Id 143, Tables 10/11

ln2020
Data from Leung & Nomoto 2020, ApJ Vol 888, Issue 2, Id 80

br2019-1
Data from Bravo, E. et al., 2019, MNRAS, 482, Issue 4, 4346–4363, Table 3

br2019-2
Data from Bravo, E. et al., 2019, MNRAS, 482, Issue 4, 4346–4363, Table 4

gro2021-1
Data from Gronow, S. et al., 2021, A&A, Tables 3/A10 He+Core detonations

gro2021-2
Data from Gronow, S. et al., 2021, A&A, Tables 4/A8 He+Core detonations

mor2018-1
Data from Mori, K. et al, 2018, ApJ, 863:176 W7

mor2018-2
Data from Mori, K. et al, 2018, ApJ, 863:176 WDD2

3.5 Integration step

By default integration steps are constant in *log(t)* but this behavior can be changed via the *integration_step* setting, that can take these values:

logt
Integration step is constant in *log(t)*, so it is smaller for short-lived stars and gradually increases when time increases (stellar mass decreases). The total number of steps should be set using the *total_time_steps* setting

t
Integration step is constant in *t*. Less efficient than log(t) but can be used to study specific intervals. Should be tuned with the *total_time_steps* setting

two_steps_t
The integration will use two time steps: [half the lifetime of a 100 solar masses star for the given metallicity] as time step for stars bigger than 4 solar masses, and 100 times that for less massive stars. If this option is selected the *total_time_steps* setting is ignored

fixed_n_steps
The integration will take exactly the number of time steps specified in the next two settings (*integration_steps_stars_smaller_than_4Msun* and *integration_steps_stars_bigger_than_4Msun*)

integration_steps_stars_bigger_than_4Msun
integer number of integration time steps for m = 4Msun to m_max. This option is ignored unless *integration_step* value is *fixed_n_steps*

integration_steps_stars_smaller_than_4Msun
integer number of integration time steps for m = m_min to 4Msun. This option is ignored unless *integration_step* value is *fixed_n_steps*

3.6 Ejected data file

The `expelled_elements_filename` setting should be a valid path of a text file containing data for expelled elements per stellar mass.

Format:

The file should include a row of data for each stellar mass. Structure of each row should be:

- First column: **stellar mass**
- 2nd to 19th columns: expelled mass of element i where i is in the following ordered list

  H, D, He3, He4, C12, C13, N14primary, n.r., O16, Ne, Mg, Si, S, Ca, Fe, remnants, C13secondary, N14secondary

This data will be used internally to interpolate/extrapolate values for all the mass range of the model.

There is a special case: When using the combination of yields from Cristallo et al. 2011 (for low mass stars) + Limongi & Chieffi 2012 (for massive stars) data needs to be corrected because for non solar metalicities they don't follow solar scale. Starmatrix will perform this correction automatically if the name of the file with the ejected data includes 'CRILIM' or 'CRI_LIM'.

3.7 Yield corrections

Using the `yield_corrections` setting you can specify correction factors for the yields contained in the ejected data file. This setting is a map of **key: value** pairs. The allowed keys correspond to the elements included in the ejected data file:

H, **D**, **He3**, **He4**, **C12**, **C13**, **N14p**, **n.r.**, **O16**, **Ne**, **Mg**, **Si**, **S**, **Ca**, **Fe**, **remnants**, **C13s** and **N14s**

Example:

If you want to multiply all magnesium data by 2, and all Sulfur data by 0.87 your settings file should include:

```
yield_corrections:
    mg: 2
    s: 0.87
```

3.8 Default values

If Starmatrix is run with an empty configuration file or using the file generated by the command `starmatrix --generate-config` with no modifications the set of default values that will be used for each parameter are the following:

z
: 0.02

sol_ab
: as09

imf
: kroupa

imf_m_low
: 0.15

imf_m_up
: 100

m_min
: 0.98

m_max
: 40.0

total_time_steps
: 300

binary_fraction
: 0.15

dtd_sn
: rpl

sn_yields
: iwa1998

output_dir
: results

matrix_headers
: yes

return_fractions
: False

integration_step
: logt

dtd_correction_factor
: 1.0 # No corrections

deprecation_warnings
: True

expelled_elements_filename
: data for z=0.02 from Gavilan et al, and Chieffi & Limongi

yield_corrections
: # No corrections

This set of values is a mix of solar values were possible and common options from the literature for the Milky Way for star masses from 0.98 to 40 Msun without correcting yields or SN factors.

CHAPTER

FOUR

OUTPUT FILES

Runnign Starmatrix produces three text files:

qm-matrices
: The main output file containing Q matrices for each mass interval with the ejections for 15 chemical elements. Expressed as stellar mass fractions.

mass_intervals
: The intervals of mass used for each time step of the integration.

imf_supernova_rates
: The resulting supernovae rates for each mass interval.

4.1 Location

The output files are created in the directory specified in the settings file with the `output_dir` parameter. If empty or non-present a new `results` directory will be created in the working path and the output files will be generated there.

4.2 Qm matrices file

The `qm-matrices` file contains all the Q-matrices of elements, one for each of the intervals in the configured mass range. Each Q-matrix is 15 rows x 9 columns of data, where every entry represents the stellar mass fraction originally in form of the element in the column which has been processed and ejected as the element in the row.

The element production matrix has this structure:

	H	D	He3	He4	C12	O16	N14	C13	nr
H									
D									
He3									
He4									
C12									
O16									
N14									
C13									
nr									
Ne									
Mg									
Si									
S									
Ca									
Fe									

So, for example, the data in the 14th row and 4th column is the Calcium created from Helium 4.

By default every matrix has a header line with the corresponding mass interval. This headers can be disabled via the configuration file setting the value for `matrix_headers` to *false*.

Example of a qm-matrices output file (truncated):

```
# Q matrix for mass interval: [40.0, 38.6169292113]
0.0004294859   -0.0004052298    0.0000000000    0.0000000000    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000000000    0.0000000000    0.0000000000    0.0000000000    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000000000    0.0003300456    0.0002200304    0.0000000000    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0001488990    0.0005375317    0.0003583545    0.0005783849    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000249375    0.0000374063    0.0000249375    0.0000249375    0.0004088744    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0001378250    0.0002067375    0.0001378250    0.0001378250    0.0000000000    0.
↪0004209163    0.0000000000    0.0000000000    0.0000000000
0.0000000026    0.0000000039    0.0000000026    0.0000000026    0.0001574686    0.
↪0001574686    0.0005783849    0.0001574686    0.0000000000
0.0000000044    0.0000000067    0.0000000044    0.0000000044    0.0000120419    0.
↪0000000000    0.0000000000    0.0004209163    0.0000000000
0.0000000000    0.0000000000    0.0000000000    0.0000000000    0.0002320747    0.
↪0002320747    0.0002320747    0.0002320747    0.0008104596
0.0000269545    0.0000404318    0.0000269545    0.0000269545    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000031806    0.0000047709    0.0000031806    0.0000031806    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000070027    0.0000105041    0.0000070027    0.0000070027    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000033363    0.0000050044    0.0000033363    0.0000033363    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000004043    0.0000006064    0.0000004043    0.0000004043    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
```

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```
0.0000013583    0.0000020375    0.0000013583    0.0000013583    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
# Q matrix for mass interval: [38.6169292113, 37.3257894555]
0.0004287608   -0.0004004904    0.0000000000    0.0000000000    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000000000    0.0000000000    0.0000000000    0.0000000000    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000000000    0.0003316710    0.0002211140    0.0000000000    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0001477359    0.0005330740    0.0003553827    0.0005764967    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000238159    0.0000357239    0.0000238159    0.0000238159    0.0004096646    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0001332491    0.0001998736    0.0001332491    0.0001332491    0.0000000000    0.
↪0004216718    0.0000000000    0.0000000000    0.0000000000
0.0000000027    0.0000000040    0.0000000027    0.0000000027    0.0001548248    0.
↪0001548248    0.0005764967    0.0001548248    0.0000000000
0.0000000042    0.0000000064    0.0000000042    0.0000000042    0.0000120073    0.
↪0000000000    0.0000000000    0.0004216718    0.0000000000
0.0000000000    0.0000000000    0.0000000000    0.0000000000    0.0002244840    0.
↪0002244840    0.0002244840    0.0002244840    0.0008009807
0.0000277443    0.0000416164    0.0000277443    0.0000277443    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000033832    0.0000050747    0.0000033832    0.0000033832    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000066766    0.0000100149    0.0000066766    0.0000066766    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000031411    0.0000047116    0.0000031411    0.0000031411    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000003807    0.0000005711    0.0000003807    0.0000003807    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000014330    0.0000021495    0.0000014330    0.0000014330    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
# Q matrix for mass interval: [37.3257894555, 36.1164668594]
0.0004286109   -0.0003963591    0.0000000000    0.0000000000    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000000000    0.0000000000    0.0000000000    0.0000000000    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000000000    0.0003333835    0.0002222556    0.0000000000    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0001467870    0.0005297134    0.0003531423    0.0005753979    0.0000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000227451    0.0000341176    0.0000227451    0.0000227451    0.0004109786    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0001289278    0.0001933917    0.0001289278    0.0001289278    0.0000000000    0.
↪0004229675    0.0000000000    0.0000000000    0.0000000000
0.0000000027    0.0000000041    0.0000000027    0.0000000027    0.0001524304    0.
↪0001524304    0.0005753979    0.0001524304    0.0000000000
0.0000000040    0.0000000061    0.0000000040    0.0000000040    0.0000119890    0.
↪0000000000    0.0000000000    0.0004229675    0.0000000000
0.0000000000    0.0000000000    0.0000000000    0.0000000000    0.0002173203    0.
↪0002173203    0.0002173203    0.0002173203    0.0007927182
```

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```
0.0000285566    0.0000428349    0.0000285566    0.0000285566    0.00000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000035866    0.0000053799    0.0000035866    0.0000035866    0.00000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000063649    0.0000095474    0.0000063649    0.0000063649    0.00000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000029534    0.0000044302    0.0000029534    0.0000029534    0.00000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000003581    0.0000005371    0.0000003581    0.0000003581    0.00000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
0.0000015083    0.0000022624    0.0000015083    0.0000015083    0.00000000000    0.
↪0000000000    0.0000000000    0.0000000000    0.0000000000
# Q matrix for mass interval: [36.1164668594, 34.980431972]
...
```

	H (1)	^4He (2)	^{12}C (3)	^{13}C (4)	^{14}N (5)	^{16}O (6)	nr (7)	^{20}Ne (8)	^{24}Mg (9)	^{28}Si (10)	^{32}S (11)	^{40}Ca (12)	^{56}Fe (13)
(1) H	$1-q_4$												
(2) ^4He	q_4-q_C	$1-q_C$											
(3) ^{12}C	$\chi_C w_C$	$\chi_C w_C$	$1-q_{C13s}$										
(4) ^{13}C	$\chi_{C13} w_C$	$\chi_{C13} w_C$	$q_{C13s}-q_{Ns}$	$1-q_{Ns}$									
(5) ^{14}N	$\chi_N w_C$	$\chi_N w_C$	$q_{Ns}-q_C$	$q_{Ns}-q_C$	$1-q_C$	$q_{Ns}-q_C$							
(6) ^{16}O	$\chi_O w_C$	$\chi_O w_C$				$1-q_{Ns}$							
(7) nr			w_C	w_C	w_C	w_C	$1-d$						
(8) ^{20}Ne	$\chi_{Ne} w_C$	$\chi_{Ne} w_C$						$1-d$					
(9) ^{24}Mg	$\chi_{Mg} w_C$	$\chi_{Mg} w_C$							$1-d$				
(10) ^{28}Si	$\chi_{Si} w_C$	$\chi_{Si} w_C$								$1-d$			
(11) ^{32}S	$\chi_S w_C$	$\chi_S w_C$									$1-d$		
(12) ^{40}Ca	$\chi_{Ca} w_C$	$\chi_{Ca} w_C$										$1-d$	
(13) ^{56}Fe	$\chi_{Fe} w_C$	$\chi_{Fe} w_C$											$1-d$

For a more detailed explanation on the Q-Matrix formalism see Ferrini et al. (1992) and Portinari et al. Astron. Astrophys. 334, 505-539 (1998).

4.3 Mass intervals file

Starmatrix also produces a `mass_intervals` file where all the intervals of mass used for the integration and the generation of matrices are listed.

The structure of the file is as follows:

- **A first row that contains:**
  - the initial time for the integration (corresponding with the lifetime of the more massive star for the given metallicity)
  - the finish time for the integration
  - the total steps used
  - the delta for the time steps
- **The rest of the rows list the mass intervals used and have three entries:**
  - the upper limit of the mass interval

- the lower limit of the mass interval
- a counter numbering each interval

Example of a mass_intervals output file (truncated):

```
0.004647378838923375 10.197573456196142 300 0.011137629220618409
 40.0000000000   38.6169292113  1
 38.6169292113   37.3257894555  2
 37.3257894555   36.1164668594  3
 36.1164668594   34.9804319720  4
 34.9804319720   33.9104208272  5
 33.9104208272   32.9001933247  6
 32.9001933247   31.9443472846  7
 31.9443472846   31.0381733309  8
 31.0381733309   30.1775402085  9
 30.1775402085   29.3588031220  10
 29.3588031220   28.5787297184  11
 28.5787297184   27.8344397595  12
 27.8344397595   27.1233555290  13
 27.1233555290   26.4431607448  14
 26.4431607448   25.7917662712  15
 25.7917662712   25.1672813142  16
 25.1672813142   24.5679890732  17
 24.5679890732   23.9923260413  18
 23.9923260413   23.4388643126  19
 23.4388643126   22.9062963837  20
 22.9062963837   22.3934220376  21
 22.3934220376   21.8991369736  22
 21.8991369736   21.4224229101  23
 21.4224229101   20.9623389372  24
 20.9623389372   20.5180139313  25
 20.5180139313   20.0886398802  26
 20.0886398802   19.6734659889  27
 ...
```

4.4 Supernova rates file

The last output generated when running Starmatrix is the `imf_supernova_rates` file. It is a text file with as many lines as mass intervals (i.e. integration steps) and with four columns (4 entries per line):

- The value of the initial mass funtion for the corresponding mass
- The supernova type I rate obtained for the interval
- The supernova type II rate obtained for the interval
- The total (thermal and kinetic) energy released by supernovae for the corresponding mass interval

Example of a imf_supernova_rates output file (truncated):

```
0.0008567779  0.0000000000  0.0000218023  0.0003484982
0.0008482838  0.0000000000  0.0000223459  0.0003416759
0.0008410511  0.0000000000  0.0000229093  0.0003349845
0.0008348889  0.0000000000  0.0000234913  0.0003284215
```

(continues on next page)

(continued from previous page)

```
0.0008296447  0.0000000000  0.0000240910  0.0003219844
0.0008251942  0.0000000000  0.0000247076  0.0003156711
0.0008214358  0.0000000000  0.0000253405  0.0003094791
0.0008182850  0.0000000000  0.0000259894  0.0003034063
0.0008156711  0.0000000000  0.0000266538  0.0002974504
0.0008135345  0.0000000000  0.0000273337  0.0002916091
0.0008118243  0.0000000000  0.0000280287  0.0002858805
0.0008104971  0.0000000000  0.0000287388  0.0002802624
0.0008095155  0.0000000000  0.0000294640  0.0002747526
0.0008088470  0.0000000000  0.0000302041  0.0002693493
0.0008084634  0.0000000000  0.0000309592  0.0002640503
0.0008083398  0.0000000000  0.0000317294  0.0002588538
0.0008084545  0.0000000000  0.0000325146  0.0002537577
0.0008087882  0.0000000000  0.0000333149  0.0002487603
0.0008093238  0.0000000000  0.0000341304  0.0002438597
0.0008100461  0.0000000000  0.0000349613  0.0002390540
0.0008109415  0.0000000000  0.0000358075  0.0002343415
0.0008119978  0.0000000000  0.0000366693  0.0002297203
0.0008132041  0.0000000000  0.0000375468  0.0002251888
0.0008145505  0.0000000000  0.0000384401  0.0002207453
0.0008160280  0.0000000000  0.0000393493  0.0002163881
0.0008176285  0.0000000000  0.0000402747  0.0002121156
0.0008193447  0.0000000000  0.0000412164  0.0002079262
0.0008211698  0.0000000000  0.0000421745  0.0002038182
0.0008230977  0.0000000000  0.0000431492  0.0001997903
0.0008251229  0.0000000000  0.0000441408  0.0001958407
0.0008272401  0.0000000000  0.0000451494  0.0001919681
...
```

CHAPTER

FIVE

EDGE

If you want to play with the latest code present in this repository even if it has not been released yet, you can do it by cloning the repo locally and instructing pip to install it:

```
$ git clone https://github.com/xuanxu/starmatrix.git
$ cd starmatrix
$ pip install -e .
```

5.1 Testing

You can then run the test suite locally using *pytest*:

```
$ pytest
```

CHAPTER

SIX

CREDITS

6.1 Authors

Starmatrix was initially developed by Juanjo Bazán

6.2 Citation

If you find Starmatrix helpful, please consider citing the Starmatrix paper:

```
@article{Bazan2022,
   doi = {10.21105/joss.04461},
   url = {https://doi.org/10.21105/joss.04461},
   year = {2022},
   publisher = {The Open Journal},
   volume = {7},
   number = {75},
   pages = {4461},
   author = {Juanjo Bazán and Mercedes Mollá},
   title = {Starmatrix: Modelling nucleosynthesis of galactic chemical elements},
   journal = {Journal of Open Source Software}
}
```

6.3 References

Starmatrix is built upon a long list of previous works from different authors/papers:

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- *Strolger et al*, 2020, ApJ, Vol 890, 2

6.4 License