



## Simulation Documentation

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# 1 Summary

The document summaries the simulations performed by Cardiff University for the STARFORMMAPPER project, and the software that we've developed to support them. In Section 2 we discuss the hydrodynamic simulations that have been carried out by Cardiff. These simulations form 'stars' – here represented by sink particles – self-consistently from a turbulent cloud of gas, and thus allow us to study the interaction of gas and stars during the star formation process. In Section 3, we introduce the code for creating the synthetic observational data, MYOSOTIS. The paper for introducing MYOSOTIS and the example of its application is published in MNRAS (<http://adsabs.harvard.edu/abs/2019MNRAS.485.3124K>). In Chapter 4, we discuss our suite of Nbody6 simulations of young star clusters using different initial parameters, e.g. total mass, half-mass radius, degree of mass segregation, fractal dimension, binary fraction and Virial parameter. Finally in chapter 5, we explain the Gaia simulation of 50 star clusters using constant and variable  $A_v$  values.

## 2 Hydro simulations with sink particles

In this section we describe the hydrodynamical simulations performed within SFM project. Unlike the pure N-body simulations, these simulations start with a cloud of turbulent gas, and form ‘stars’ represented here by sink particles self-consistently, which form at the centres of runaway gravitational collapse. These sink particles are then able to interact via each and the gas through gravitational forces only. This sink particles are thus able to accrete gas (hence their name) and thus grow in mass as the simulation evolves.

We first give an overview of the numerical method, including the details of the sink particles employed in our simulations. We then discuss the initial conditions and the snapshots have been made available on our data repository. Finally we briefly discuss the tools that we provide to read the data.

### 2.1 The fluid code

Our simulations were performed with the Arepo moving-mesh code (Springel 2010), and we ensure that the Jeans length is refined by 16 cells at all times. We also employ the barotropic equation of state (EOS) introduced in Bhattal et al (1998), in which the pressure  $p$  in the gas is connected to the density  $\rho$  via,

$$p = c_s^2 \rho \quad (1)$$

where  $c_s$  is the sound speed, which varies with density as,

$$c_s = c_{s,0} \quad \rho \leq \rho_0 ;$$

$$c_s = \left\{ \left[ (c_{s,0}^2 - c_{s,1}^2) \left( \frac{\rho}{\rho_0} \right)^{-2/3} + c_{s,1}^2 \right]^2 + \left[ \left( (c_{s,0}^2 - c_{s,1}^2) \left( \frac{\rho_1}{\rho_0} \right)^{-2/3} + c_{s,1}^2 \right) \left( \frac{\rho}{\rho_0} \right)^{\gamma-1} \right]^2 \right\}^{1/2} \quad \rho > \rho_0 ;$$

where we take  $c_{s,0}$  to be 0.45 km/s (to mimic approximately 100 K HI) with  $\rho_0 = 1 \times 10^{-20} \text{g cm}^{-3}$  to represent the density at which the cold gas starts,  $c_{s,1}$  to be 0.2 km/s to mimic 10K molecular gas,  $\rho_1$  to be  $1 \times 10^{-14} \text{g cm}^{-3}$  as the start of the opacity limit for star formation and  $\gamma = 1.4$  to mimic the heating of the gas in the optically thick regime. This EOS provides a smooth transition between 100 K gas at low densities below  $1 \times 10^{-14} \text{g cm}^{-3}$ , cooling down to 10K gas at densities above this and below the opacity limit density  $\rho_1$ , and then heating above the opacity limit.

Sink particles (Bate et al. 1994) are added in the same manner as Federrath et al. (2010), to replace dense, collapsing gas with a point mass that is able to accrete from the gas grid and interact with the simulation gravitationally. Sink particles are able to accrete only from a limited region called the accretion radius ( $r_{\text{acc}}$ ), and are only allowed to accrete the gas that is most bound to that sink. To form sinks, a gas cell above a density threshold is checked for i) whether it is a local minimum in the potential, ii) the divergence of the local velocity and acceleration are negative, iii) the gas inside the would-be accretion radius is gravitationally bound with respects to the supporting thermal and kinetic energy.

In these simulations the sink particles are formed above a density of  $4 \times 10^{-14} \text{g cm}^{-3}$  and we adopt an accretion radius of we adopt an accretion radius of 20 AU. The sink particles have a gravitational softening length of 6.7 AU. The softening of the gas cells is taken to be twice that of their size.

### 2.2 Initial conditions

Our cloud has an initial density of  $1000 \text{ cm}^{-3}$  (with respect to hydrogen nuclei), a mass of  $1000 M_{\odot}$ , and a radius of 1.9 pc. We start our simulation with 2 million Arepo cells in the cloud and embed this cloud in box with side length 9.52 pc which is represented by 200,000 Arepo particles. We enforce that an Arepo cell

must have a mass lower than  $5 \times 10^{-4} M_{\odot}$ , which over-rides any de-refinement of the grid that is attempted by the Jeans refinement/de-refinement module.

We inject turbulent motions into our initial conditions which are left to freely decay in shocks. The turbulence has a power spectrum of  $P(k) \propto k^{-4}$ , and is comprised of only solenoidal modes (achieved via Helmholtz decomposition). The level of turbulent kinetic energy is initially set to be half that of the cloud’s gravitational energy, such that the system begins in approximate virial equilibrium, with  $\epsilon = \frac{|E_{\text{grav}}|}{E_{\text{kin}}} = 2$ . We present 3 simulations here, in which the random seed for the turbulence is changed.

## 2.3 The snapshots provided here

The snapshots provided in this data repository cover a range of times within the simulation, including before and after the formation of sink particles. The format of the snapshots is the Gadget2 (Springel 2001) “Type 2” format; more details can be found on this format in the Gadget2 user manual.

We provide a script in python to read the snapshots, which can be found in the `arepo_utils.py` module. The function `aread`, returns a python structure which contains all the properties of the file, such that `a.x` will be an array, containing a the  $x$  positions of the cells in the simulation, and `a.rho` would contain all the densities. The number of gas cells is given by `a.ngas` and the time of snapshot is stored in `a.time`. All data is given in **code units**, of

$$\begin{aligned} \text{a.unit\_leng\_cm} &= 1.00 \times 10^{17} \text{ cm} \\ \text{a.unit\_mass\_g} &= 1.991 \times 10^{33} \text{ g} \\ \text{a.unit\_time\_s} &= 1.745 \times 10^{12} \text{ s} \end{aligned}$$

which can be used to covert to the cgs system. The full list of cell properties is given by:

- `a.x(y, z)` – the coordinates of the centre of mass of the cell.
- `a.v(x, y, z)` – the centre of mass velocity of the cell (e.g. `a.vz`).
- `a.mass` – the mass of the cell.
- `a.partid` – the unique integer identifier of the cell.
- `a.u` – the specific energy of the cell.
- `a.rho` – the density of the cell.
- `a.potential` – the gravitational potential at the cell’s location
- `a.accel` – a `a.ngas`  $\times$  3 array holding the acceleration at each cell. So `a.accel[:,1]` is the  $y$ – component of the accelerations of all cells in the simulation.
- `a.dt` – the timestep that the cell is being evolved on.
- `a.divv` – the divergence of the velocity field at the cell’s location.

The number of sink particles present in the snapshot can be found from `a.sink`. Properties of the sink particles are found in the structures:

- `a.sinkx(y, z)` – the coordinates of sink particle.
- `a.sinkv(x, y, z)` – the velocity of the sink particle.

- `a.sinkmass` – the mass of the sink particle.
- `a.sinkid` – the unique integer identifier of the sink particle.

Again, all these properties (with the exception of the ID) are expressed in the code units above.

## 2.4 Image files

We also provide a series of images to accompany the snapshots. These can be found in the same directory as the snapshots themselves. The images are of the column density, in standard cgs units (so  $\text{g cm}^{-3}$  for column density and cm for position), and are  $4000 \times 4000$  pixels. The files are in the standard FITS (Flexible Image Transport System), that is common in astronomy. Note that the images have a high contrast, spanning over 7 orders of magnitude, and thus the image can only really be seen if the viewing colour table is stretched logarithmically.

## 3 MYOSOTIS

Make Your Own Synthetic ObservaTIonS (MYOSOTIS<sup>1</sup>), an IDL<sup>2</sup> publicly accessible code<sup>3</sup> written tool for creating synthetic imaging and spectroscopic data of space and ground-based telescopes as well as custom (user-defined) instruments within any FOV. The stellar and interstellar medium information (position, mass, velocity, metallicity, age, gas density) should be provided by the user. The user can choose different filters from a list of provided filters or define a new filter, to suit the observational instrument that they want to mimic (see <http://svo2.cab.inta-csic.es/theory/fps/>). Knowing the age and mass of the stars, their stellar parameters ( $T_{eff}$ ,  $\log g$  and  $\log L$ ) are estimated using PARSEC evolutionary models. Knowing the stellar parameters, a proper SED will be selected for each star, and finally stellar fluxes are estimated within a given filter using that SED. If there is an extinction, then  $A_\lambda$  is estimated (using `EXTmodels`) in each wavelength channel. User can always update the library of the Evolutionary and atmosphere models. Even for each input star, User can use her/his own SEDs.

The observing conditions, i.e. seeing, Strehl-Ratio (SR), detector's pixel scale of a given instrument, FOV, observer's line-of-sight and finally the angular resolution of the telescope can be defined in MYOSOTIS. Since most of the instruments can not achieve their theoretical optimum resolution ( $\sim \lambda/\text{Diameter}$ ), the user can also define their own resolution. The estimated flux of stellar sources spreads on the detector using a 2D point spread function (PSF) whose full width at half maximum (FWHM) is equal to the resolution. The user can choose a Gaussian distribution or an Airy pattern for the PSF of stellar sources. The extinction can be applied on the output data, knowing the column density of the gas in front of each source. This extinction could be uniform, patchy, or taken from a full 3D smoothed particle hydrodynamics (SPH) simulation data.

### 3.1 Input parameters

- `Project-name` : Name of the project chosen by the user
- `filestar` : name of the file contains 10 columns of stellar sources information:  
 $X[\text{pc}], Y[\text{pc}], Z[\text{pc}], V_x[\text{km/s}], V_y[\text{km/s}], V_z[\text{km/s}], \text{Mass}[M_\odot], \text{Logage}[\text{yr}], \text{Metallicity}, \text{gasdensity}[M_\odot/\text{pc}^2]$   
 This file contains 3D position and velocity of stars (first 6 columns) and their mass, Log(age), metallicity and gas column density in front of each star (columns 7 to 10 respectively). This file can be produced from the result of N-body simulations of star clusters or manually by the user. There is no limitation

<sup>1</sup>contact: [KhorramiZ@cardiff.ac.uk](mailto:KhorramiZ@cardiff.ac.uk)

<sup>2</sup>Written in IDL version 8.5.1 and being developed in Python as well.

<sup>3</sup><https://github.com/zkhorrami/MYOSOTIS>

for the number of stars. The stars can have different ages or metallicities which is useful specifically for the simulation of clusters with different populations. Zero values can be put for the velocities and gas density in front of each star, If user do not have any information about them. The Doppler effect will NOT be applied if the velocities have zero values. If gas density (column 10) has zero values, then it means there is no extinction in the line-of-sight of the observer unless the information of the gas is provided in `filecloud` (see next output).

- **filecloud** : name of the file contains 8 columns of the cloud's information:  
`X[pc], Y[pc], Z[pc], Vx[km/s], Vy[km/s], Vz[km/s], Mass[M⊙], smoothing-length[pc]`  
 This file contains cloud particle's 3D position and velocity (columns 1 to 6) and the particle mass and smoothing length (column 7 and 8), which are the typical output of the SPH simulations. If user do not have information about the gas cloud from SPH simulations, they can simply use `ColumnDensities='user'` and use the column density values in the last column of `filestar`.
- **ColumnDensities**: column density of the gas cloud in front of stars.  
`'sph'`: reads it from the `filecloud` (provided by the SPH simulations)  
`'user'`: reads it from the `filestar`, last column in the unit of  $[M_{\odot}/pc^2]$   
 If there is no extinction in the simulations, user should set `ColumnDensities='user'` and put Zero values in the last column of `filestar`.
- **filter** : name of the instrument's filter which contains 2 columns of:  
`Lambda[A], filter-transparency`  
 User can choose any filter from the provided list of filters or can define her/his own filter. Full list of provided filters are listed in the Filter folder. For example if user wants to use the first filter in the list (2MASS/H) she/he should set `filter='Filters/2mass/2MASS-2MASS.H.dat'`
- **distance** : distance of the center of the simulation  $[X=0, Y=0, Z=0]$  from the observer [pc].  
 Note that the X,Y,Z positions in the `filestar` and `filecloud` are respect to the center of the simulation. So the final distance of each star will be calculated by adding `distance` plus their distance from the center (in the line-of-sight of the observer). So even if all the stars have the same intrinsic flux, in the synthetic image they will not have the same flux since they have different locations from the center-of-simulation.
- **EXTmodel** : model to be used for estimating extinction in different wavelengths ( $A_{\lambda}$ ).  
`'Fmodel'`: The code uses a function to calculate extinction in a given wavelength knowing optical extinction values ( $A_V$  and  $R_V$ ). This function uses the average extinction curve in the optical-through-IR range (0.125 - 3.333  $\mu m$ ) which is reproduced with a cubic spline and a set of anchor points from Fitzpatrick (1999).  
`'Dmodel'`: The code uses synthetic extinction curves <sup>4</sup> from Draine (2003a,b,c); Li & Draine (2001); Weingartner & Draine (2001). Extinction, absorption, albedo,  $\langle \cos(\theta) \rangle$ , and  $\langle \cos^2(\theta) \rangle$  have been calculated for wavelengths from 1 cm (30 GHz) to 1 Angstrom (12.4 keV), for selected mixtures of carbonaceous grains and amorphous silicate grains. These models cover three values of  $R_V$ , 3.1, 4.0 and 5.5.
- **Rv** :  $A_V/E(B-V)$  constant value, for example should be set to 3.1 for MW Galaxy. If user chooses `EXTmodel='Fmodel'` then any value can be chosen for  $R_V$ , but for the `EXTmodel='Dmodel'` user is limited to choose  $R_V$  of 3.1, 4.0 and 5.5 only.
- **res** : pixel sampling of the instrument [arcsecond/pix]
- **fov<sub>x</sub>, fov<sub>y</sub>** : Field of view in x and y [arcsecond]
- **fwhm** : angular resolution of the observational instrument [arcsecond]. The optimum resolution for a single dish telescope is about  $\lambda/D$ . If the telescope does not have adaptive optics and its resolution is worse than atmospheric turbulence, this parameter should be set to the seeing value (see Figure 1).

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<sup>4</sup>[www.astro.princeton.edu/~draine/dust/dustmix.html](http://www.astro.princeton.edu/~draine/dust/dustmix.html)

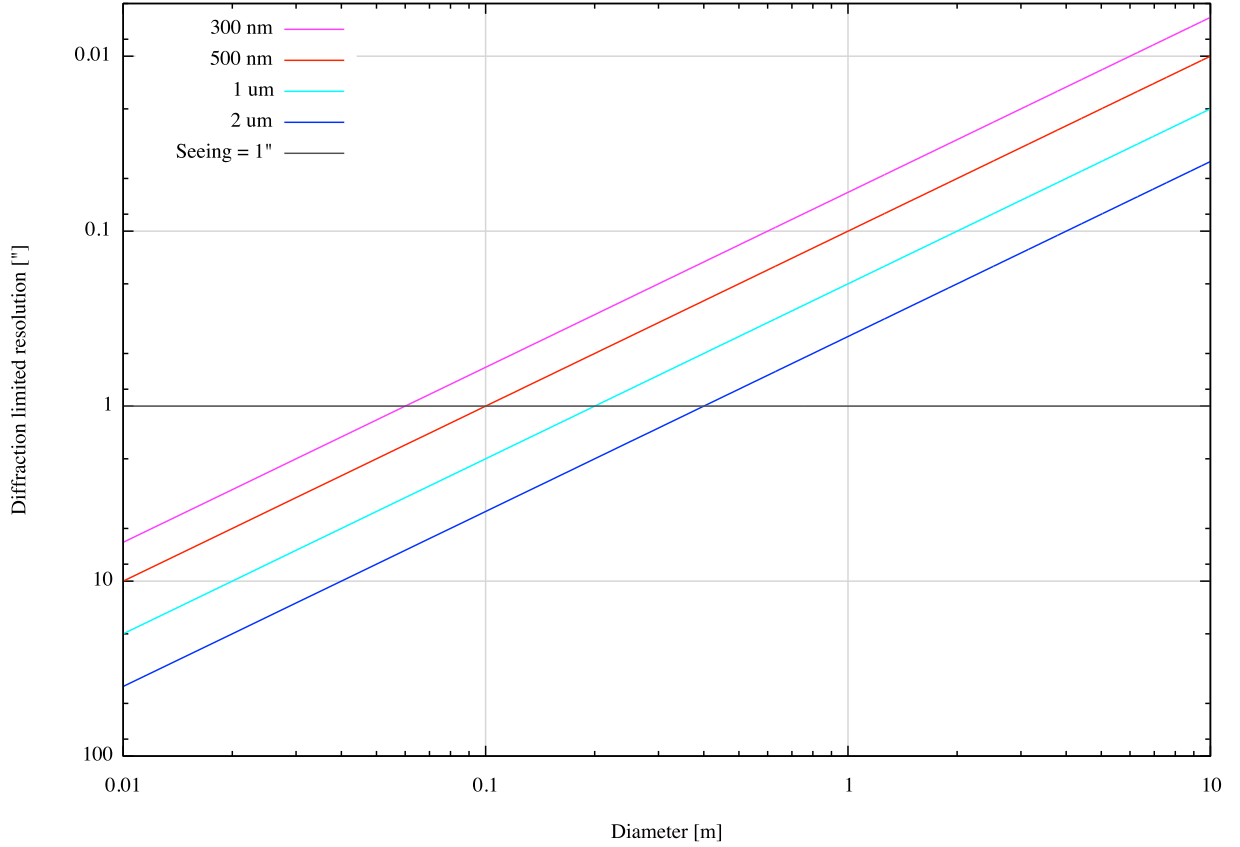


Figure 1: Diffraction limited resolution of telescopes with different diameter in four different wavelengths: 300, 500, 1000 and 2000 nm

- **spectroscopy** : 'yes' providing a cube data in wavelength range of  $\lambda_{min}[A] - -\lambda_{max}[A]$  with the spectral resolution of R. 'no' does not provide any spectroscopic data.
- **lminspec** : minimum value of the wavelength for spectroscopy ( $\lambda_{min}[A]$ ).
- **lmaxspec** : maximum value of the wavelength for spectroscopy ( $\lambda_{max}[A]$ ).
- **Rspec** : spectral resolution of the instrument ( $R = \frac{\lambda}{\Delta\lambda}$ ).
- **OBtreatment** : 'yes' uses TLUSTY SEDs for O and B type stars
- **Adaptiveoptics** : 'yes' the flux of the star will distribute partially in the airy pattern and the halo.
- **SR** : Strehl ratio, value between 0.0-1.0. If SR=1.0 the images are as perfect as space telescope's images.
- **seeing** : atmospheric resolution (FWHM of the halo) [arcsecond]
- **velocitydis** : 'yes' will apply Doppler shift in the spectroscopic data, 'no' does not apply any Doppler shift in the spectra.
- **alpha\_i, beta\_i, gamma\_i** : Euler angles for rotation [degree], rotation around x, y and z, respectively. If all of them are zero, then output image is X-Y plane.  
 [0, 0, 0] -> X-Y  
 [90, 0, 0] -> X-Z  
 [0, 90, 0] -> Y-Z

- **SNR:** Signal to Noise ratio for the faintest star (e.g. 2.0, the noise will be as high as twice of the maximum flux value of the faintest star in the FOV,  $noise = \frac{F/(2\pi\sigma^2)}{SNR}$ ,  $F$  =flux of the faintest star,  $\sigma^2 = \frac{FWHM^2}{4 \text{Ln}(2)}$ ).
- **noise2add:** noise to be added on the image in the unit of  $[flux/pix^2] = [erg/cm^2/s/A/pix^2]$  ONLY if the SNR is 0.0

## 3.2 Output

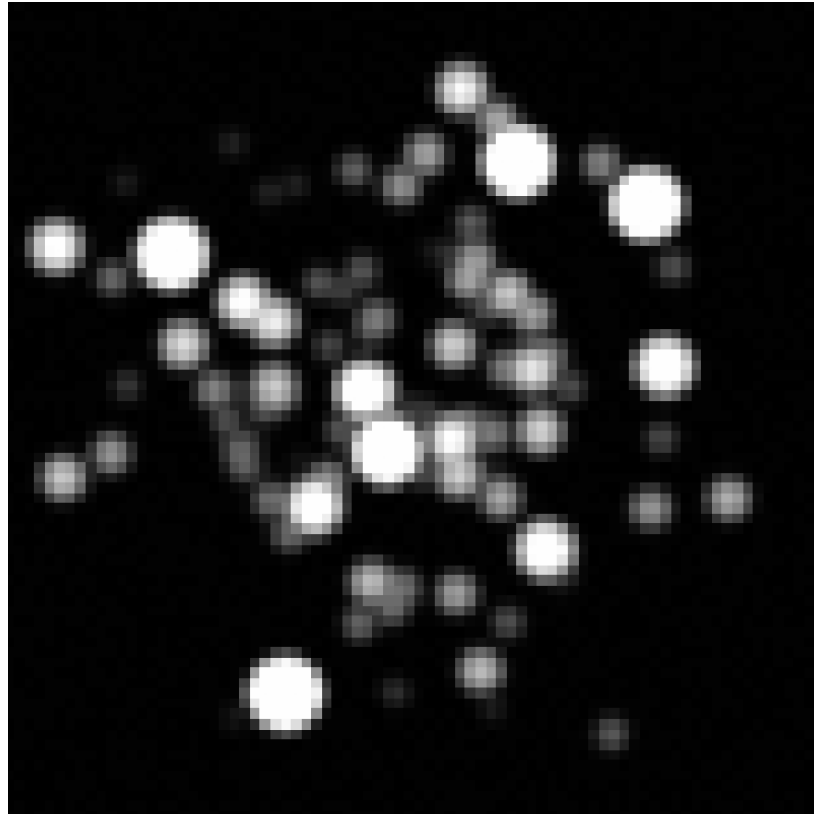
- **\*\_image.fits** : 2D fits image
- **\*\_star\_info.txt** : contains the information of the stellar sources in the FoV This file contains 11 columns and each line shows the information of a given star.  
mass[M<sub>⊙</sub>], Logage[yr], Metallicity, LogTeff[K], Logg, LogL/L<sub>⊙</sub>, A<sub>V</sub>, mag, X[pix], Y[pix], assignedSED  
If spectroscopy='yes' the two other outputs:
- **\*\_cube\_spectra.fits** : 3D cube, X-Y is the position of stellar sources, Z is flux in different wavelengths
- **\*\_Lambda.txt** : the wavelengths [Å] which is used for the 3rd dimension of the spectral-cube

## 3.3 Example

In the folder "Examples" we created three files: Teststar1.txt , Teststar2.txt , Testcloud1e3.txt

- **Teststar1.txt** : This file can be used for filestar. There are 100 stars within a radius of 1pc with a total mass of about 104 M<sub>⊙</sub>. These stars all have the same age (2Myr) and metallicity (Z=0.015 Z<sub>⊙</sub>) without any extinction (cloud density values are zero).
- **Teststar2.txt** : This file can be used for filestar. Similar to Teststar1.txt, except that stars have three different ages of 1.0, 2.0 and 5 Myr and the cloud column density (last column) has random values between 20-80 [M<sub>⊙</sub>/pc<sup>2</sup>] for stellar sources.
- **Testcloud1e3.txt** : This is an example of the filecloud, generated by standard SPH code. This cloud contains 10<sup>5</sup> particles with mass of 0.01 M<sub>⊙</sub>, so the total mass of the cloud is 10<sup>3</sup> M<sub>⊙</sub>. This cloud has a Plummer density profile within a radius of 5.0pc.





pro MYOSOTIS

```

project_name = 'test2' ; Name of the project
filestar = 'Examples/Teststar2.txt' ; Star's information file (should be 10 columns)
filecloud= 'NoCloud' ; Cloud's information file (should be 8 columns). Will be needed if Columndensities = 'sph'
Columndensities= 'user' ; 'sph': reads the cloud information file, 'user': reads it from the filestar, last column in the unit of [Msun/pc2]

filter = 'Filters/generic/johnson/Generic-Johnson.V.dat' ;choose the path of your favourite filter!

res = 0.1 ; pixel resolution [arcsec/pix]
fovx = 8 ; Field-of-view X [arcsec]
fovy = 8 ; Field-of-view Y [arcsec]
fwhm = 0.2 ; FWHM of the PSF, angular resolution of the instrument
PSFtype= 'gaussian' ; 'airy' Type of PSF for distribution of the stellar fluxes on the detector: 'gassian' or 'airy'

distance = 50000. ; Distance of the observer from the reference in filestar and filecloud [pc]
EXTmodel = 'Dmodel' ; Extinction model, choose either 'Dmodel' OR 'Fmodel' (see the manual for more information on these models)
Rv = 3.1 ; Rv should be 3.1 or 4.0 or 5.5 if EXTmodel='Dmodel', otherwise can be set to any value.

OBtreatment = 'yes' ; Uses TLUSTY SEDs for stars with Teff > 15000 K
Adaptiveoptics = 'no' ; Using of adaptive optics
SR = 1.0 ; Strehl Ratio, should be between 0.0 - 1.0
seeing = 0.8 ; Seeing [arcsec]

spectroscopy = 'no' ; Spectroscopy output, choose 'yes' or 'no'
lminspec = 3900. ; Minimum wavelength [A] should be set within your filter transparency
lmaxspec = 5100. ; Maximum wavelength [A]
Rspec = 700 ; Spectral resolution (please check your SED library, should not be larger than the resolution of the SEDs)

velocitydis = 'no' ; 'yes' or 'no' : Adding Doppler shift on the spectra according to the velocity of the stars

;Euler angles for rotation [degree]:
;if all of them are zero, then outout image is X-Y
;[0,0,0] --> X-Y
;[90,0,0] --> X-Z
;[0,90,0] --> Y-Z
alpha = 0 ; rotation around x [degree]
bettai = 0 ; rotation around y [degree]
gamma = 0 ; rotation around z [degree]

SNR = 5.0 ; Signal to Noise ratio for the faintest star in the FOV

```

Figure 2: Top: Example of the image provided by MYPOSOTIS in logscale. The filestar is Teststar2.txt from the examples. The initial parameters chosen to create this image (screenshot from IDL code) is given in the bottom.

## 4 Series of Nbody6 simulations

### 4.1 Input parameters

Series of Nbody6 simulation of star clusters has been done within the StarFormMapper (SFM) project. The dynamical and stellar evolution of these star clusters have been studied within 100Myr. These star clusters have different initial parameters. The initial set-up of these clusters are done using Mcluster tool (<https://github.com/ahwkuepper/mcluster>).

The basic initial physical parameters of these star clusters are:

- Total mass of the star cluster:  $10^3$  and  $10^4 M_{\odot}$
- Mass function: Kroupa (2001)
- Mass range:  $(0.1-300) M_{\odot}$
- Density profile: Plummer
- Half-mass radius: 0.1, 0.5 and 1.0 pc
- Degree of mass segregation: 0.0 (no-segregation) and 1.0 (totally segregated)
- Virial ratio: 0.5 (equilibrium) and 0.3 (collapsing)
- Fractal Dimension: 3.0 (symmetric) and 2.0
- Stellar evolution: Eggleton, Tout & Hurley
- Metallicity: Solar ( $Z=0.02$ )
- No Galactic tidal field
- $T_{critical} = 100$  Myr
- Output interval = 1.0 Myr

Binary parameters are:

- Primordial binary fraction ( $F_{bin}$ ) = 0.0, 0.5  
number of binary systems =  $0.5 N F_{bin}$
- Pairing is random but separate pairing for components with masses  $m > M_{sort}$
- $M_{sort} = 5.0 M_{\odot}$
- Semi-major axis distribution: based on Kroupa (1995) period distribution for  $M < M_{sort}$ ; based on Sana et al. (2012); Oh, S., Kroupa, P., & Pflamm-Altenburg, J. (2015) period distribution for  $M > M_{sort}$
- Use period distribution for massive binaries with  $M_{primary} > M_{sort}$  from Sana & Evans (2011)
- binary star evolution using BSE (Hurley, Tout & Pols 2002)

Other code parameters are:

- Energy-check time step = 0.2 Myr

- Removal of escapers: regular removal at  $2R_{tide}$  and output in ESC
- Use random kick velocity and present-day escape velocity to determine retention of compact remnants and evolved binary components

Our sets of simulated clusters differ in Total mass, half-mass radius, binary fraction, initial mass segregation, fractal dimension and Virial ratio. The variables values and the simulation name are given in the following tables. The location of each simulation, in Quasars center, is also provided in the last column of these Tables.

## 4.2 Output

In the location folder of each simulation, there is one folder with the name of the simulation. In this folder the basic information of stars in each time-step is given. There are four types of files:

1) \*-all (information on the single stars in different time-steps), 2) \*-com (information of the center-of-mass of the multiple systems), 3) \*-bin (information of the binary systems), and 4) \*-higher (information on the higher-order systems, with more than one companions):

The detail of the output of these three type of files are given below.

1) \*-all files contain 12 columns of Name, X, Y, Z, VX, VY, VZ, KSTAR, ZLMSTY, RADIUS, MASS, Ncompanions

Name: ID of the stars. User can track a star in different time-steps

X,Y,Z: Position of stars respect to the center-of-mass of the cluster, in Parsec

VX, VY, VZ: Velocity of stars, in Km/s

KSTAR: Stellar evolution types

0 : Low main sequence ( $M < 0.7$ ).

1 : Main sequence.

2 : Hertzsprung gap (HG).

3 : Red giant.

4 : Core Helium burning.

5 : First AGB.

6 : Second AGB.

7 : Helium main sequence.

8 : Helium HG.

9 : Helium GB.

10 : Helium white dwarf.

11 : Carbon-Oxygen white dwarf.

12 : Oxygen-Neon white dwarf.

13 : Neutron star.

Name	Fractal Dim	Seg Degree	Binary fraction	$M_{tot}$ [ $M_{\odot}$ ]	$R_{hm}$ [ $pc$ ]	Q	Location pure_nbody_sims/Total_Mass_1000Msun/
D30S00bin00M103r01	3.0	0.0	0.0	$10^3$	0.1	0.5	Virial_equilibrium_Q0p5/R01/
D30S00bin05M103r01	3.0	0.0	0.5	$10^3$	0.1	0.5	
D30S10bin00M103r01	3.0	1.0	0.0	$10^3$	0.1	0.5	
D30S10bin05M103r01	3.0	1.0	0.5	$10^3$	0.1	0.5	
D20S00bin05M103r01	2.0	0.0	0.0	$10^3$	0.1	0.5	
D20S00bin05M103r01	2.0	0.0	0.5	$10^3$	0.1	0.5	
D20S10bin00M103r01	2.0	1.0	0.0	$10^3$	0.1	0.5	
D20S10bin05M103r01	2.0	1.0	0.5	$10^3$	0.1	0.5	
D30S00bin00M103r05	3.0	0.0	0.0	$10^3$	0.5	0.5	Virial_equilibrium_Q0p5/R05/
D30S00bin05M103r05	3.0	0.0	0.5	$10^3$	0.5	0.5	
D30S10bin00M103r05	3.0	1.0	0.0	$10^3$	0.5	0.5	
D30S10bin05M103r05	3.0	1.0	0.5	$10^3$	0.5	0.5	
D20S00bin05M103r05	2.0	0.0	0.0	$10^3$	0.5	0.5	
D20S00bin05M103r05	2.0	0.0	0.5	$10^3$	0.5	0.5	
D20S10bin00M103r05	2.0	1.0	0.0	$10^3$	0.5	0.5	
D20S10bin05M103r05	2.0	1.0	0.5	$10^3$	0.5	0.5	
D30S00bin00M103r10	3.0	0.0	0.0	$10^3$	1.0	0.5	Virial_equilibrium_Q0p5/R10/
D30S00bin05M103r10	3.0	0.0	0.5	$10^3$	1.0	0.5	
D30S10bin00M103r10	3.0	1.0	0.0	$10^3$	1.0	0.5	
D30S10bin05M103r10	3.0	1.0	0.5	$10^3$	1.0	0.5	
D20S00bin05M103r10	2.0	0.0	0.0	$10^3$	1.0	0.5	
D20S00bin05M103r10	2.0	0.0	0.5	$10^3$	1.0	0.5	
D20S10bin00M103r10	2.0	1.0	0.0	$10^3$	1.0	0.5	
D20S10bin05M103r10	2.0	1.0	0.5	$10^3$	1.0	0.5	
D30S00bin00M103r01	3.0	0.0	0.0	$10^3$	0.1	0.3	Virially_cold_Q0p3/R01/
D30S00bin05M103r01	3.0	0.0	0.5	$10^3$	0.1	0.3	
D30S10bin00M103r01	3.0	1.0	0.0	$10^3$	0.1	0.3	
D30S10bin05M103r01	3.0	1.0	0.5	$10^3$	0.1	0.3	
D20S00bin05M103r01	2.0	0.0	0.0	$10^3$	0.1	0.3	
D20S00bin05M103r01	2.0	0.0	0.5	$10^3$	0.1	0.3	
D20S10bin00M103r01	2.0	1.0	0.0	$10^3$	0.1	0.3	
D20S10bin05M103r01	2.0	1.0	0.5	$10^3$	0.1	0.3	
D30S00bin00M103r05	3.0	0.0	0.0	$10^3$	0.5	0.3	Virially_cold_Q0p3/R05/
D30S00bin05M103r05	3.0	0.0	0.5	$10^3$	0.5	0.3	
D30S10bin00M103r05	3.0	1.0	0.0	$10^3$	0.5	0.3	
D30S10bin05M103r05	3.0	1.0	0.5	$10^3$	0.5	0.3	
D20S00bin05M103r05	2.0	0.0	0.0	$10^3$	0.5	0.3	
D20S00bin05M103r05	2.0	0.0	0.5	$10^3$	0.5	0.3	
D20S10bin00M103r05	2.0	1.0	0.0	$10^3$	0.5	0.3	
D20S10bin05M103r05	2.0	1.0	0.5	$10^3$	0.5	0.3	
D30S00bin00M103r10	3.0	0.0	0.0	$10^3$	1.0	0.3	Virially_cold_Q0p3/R10/
D30S00bin05M103r10	3.0	0.0	0.5	$10^3$	1.0	0.3	
D30S10bin00M103r10	3.0	1.0	0.0	$10^3$	1.0	0.3	
D30S10bin05M103r10	3.0	1.0	0.5	$10^3$	1.0	0.3	
D20S00bin05M103r10	2.0	0.0	0.0	$10^3$	1.0	0.3	
D20S00bin05M103r10	2.0	0.0	0.5	$10^3$	1.0	0.3	
D20S10bin00M103r10	2.0	1.0	0.0	$10^3$	1.0	0.3	
D20S10bin05M103r10	2.0	1.0	0.5	$10^3$	1.0	0.3	

Name	Fractal Dim	Seg Degree	Binary fraction	$M_{tot}$ [ $M_{\odot}$ ]	$R_{hm}$ [ $pc$ ]	Q	Location /pure_nbody_sims/Total_Mass_10000Msun/
D30S00bin00M104r01	3.0	0.0	0.0	$10^4$	0.1	0.5	Virial_equilibrium_Q0p5/R01/
D30S00bin05M104r01	3.0	0.0	0.5	$10^4$	0.1	0.5	
D30S10bin00M104r01	3.0	1.0	0.0	$10^4$	0.1	0.5	
D30S10bin05M104r01	3.0	1.0	0.5	$10^4$	0.1	0.5	
D20S00bin05M104r01	2.0	0.0	0.0	$10^4$	0.1	0.5	
D20S00bin05M104r01	2.0	0.0	0.5	$10^4$	0.1	0.5	
D20S10bin00M104r01	2.0	1.0	0.0	$10^4$	0.1	0.5	
D20S10bin05M104r01	2.0	1.0	0.5	$10^4$	0.1	0.5	
D30S00bin00M104r05	3.0	0.0	0.0	$10^4$	0.5	0.5	Virial_equilibrium_Q0p5/R05/
D30S00bin05M104r05	3.0	0.0	0.5	$10^4$	0.5	0.5	
D30S10bin00M104r05	3.0	1.0	0.0	$10^4$	0.5	0.5	
D30S10bin05M104r05	3.0	1.0	0.5	$10^4$	0.5	0.5	
D20S00bin05M104r05	2.0	0.0	0.0	$10^4$	0.5	0.5	
D20S00bin05M104r05	2.0	0.0	0.5	$10^4$	0.5	0.5	
D20S10bin00M104r05	2.0	1.0	0.0	$10^4$	0.5	0.5	
D20S10bin05M104r05	2.0	1.0	0.5	$10^4$	0.5	0.5	
D30S00bin00M104r10	3.0	0.0	0.0	$10^4$	1.0	0.5	Virial_equilibrium_Q0p5/R10/
D30S00bin05M104r10	3.0	0.0	0.5	$10^4$	1.0	0.5	
D30S10bin00M104r10	3.0	1.0	0.0	$10^4$	1.0	0.5	
D30S10bin05M104r10	3.0	1.0	0.5	$10^4$	1.0	0.5	
D20S00bin05M104r10	2.0	0.0	0.0	$10^4$	1.0	0.5	
D20S00bin05M104r10	2.0	0.0	0.5	$10^4$	1.0	0.5	
D20S10bin00M104r10	2.0	1.0	0.0	$10^4$	1.0	0.5	
D20S10bin05M104r10	2.0	1.0	0.5	$10^4$	1.0	0.5	
D30S00bin00M104r01	3.0	0.0	0.0	$10^4$	0.1	0.3	Virially_cold_Q0p3/R01/
D30S00bin05M104r01	3.0	0.0	0.5	$10^4$	0.1	0.3	
D30S10bin00M104r01	3.0	1.0	0.0	$10^4$	0.1	0.3	
D30S10bin05M104r01	3.0	1.0	0.5	$10^4$	0.1	0.3	
D20S00bin05M104r01	2.0	0.0	0.0	$10^4$	0.1	0.3	
D20S00bin05M104r01	2.0	0.0	0.5	$10^4$	0.1	0.3	
D20S10bin00M104r01	2.0	1.0	0.0	$10^4$	0.1	0.3	
D20S10bin05M104r01	2.0	1.0	0.5	$10^4$	0.1	0.3	
D30S00bin00M104r05	3.0	0.0	0.0	$10^4$	0.5	0.3	Virially_cold_Q0p3/R05/
D30S00bin05M104r05	3.0	0.0	0.5	$10^4$	0.5	0.3	
D30S10bin00M104r05	3.0	1.0	0.0	$10^4$	0.5	0.3	
D30S10bin05M104r05	3.0	1.0	0.5	$10^4$	0.5	0.3	
D20S00bin05M104r05	2.0	0.0	0.0	$10^4$	0.5	0.3	
D20S00bin05M104r05	2.0	0.0	0.5	$10^4$	0.5	0.3	
D20S10bin00M104r05	2.0	1.0	0.0	$10^4$	0.5	0.3	
D20S10bin05M104r05	2.0	1.0	0.5	$10^4$	0.5	0.3	
D30S00bin00M104r10	3.0	0.0	0.0	$10^4$	1.0	0.3	Virially_cold_Q0p3/R10/
D30S00bin05M104r10	3.0	0.0	0.5	$10^4$	1.0	0.3	
D30S10bin00M104r10	3.0	1.0	0.0	$10^4$	1.0	0.3	
D30S10bin05M104r10	3.0	1.0	0.5	$10^4$	1.0	0.3	
D20S00bin05M104r10	2.0	0.0	0.0	$10^4$	1.0	0.3	
D20S00bin05M104r10	2.0	0.0	0.5	$10^4$	1.0	0.3	
D20S10bin00M104r10	2.0	1.0	0.0	$10^4$	1.0	0.3	
D20S10bin05M104r10	2.0	1.0	0.5	$10^4$	1.0	0.3	

14 : Black hole.

15 : Massless supernova remnant.

ZLMSTY: stellar luminosity  $L/L_{\odot}$

RADIUS: stellar radius  $R/R_{\odot}$

MASS: stellar mass  $M/M_{\odot}$

Ncompanions: number of the companions. e.g. 0: single star, 1: binary system, 2 or higher: multiple systems

2) \*-com (center-of-mass) files contain 11 columns of Name, X, Y, Z, VX, VY, VZ, KSTAR, ZLMSTY, RADIUS, MASS

Name: ID of the center of masses. It should be larger than the total number of stars.

X,Y,Z: Position of center-of-masses respect to the center-of-mass of the cluster, in Parsec

VX, VY, VZ: Velocity of center-of-masses, in Km/s

KSTAR, ZLMSTY, RADIUS (zero values)

MASS: total mass of the multiple system.

2) \*-com (center-of-mass) files contain 11 columns of Name, X, Y, Z, VX, VY, VZ, KSTAR, ZLMSTY, RADIUS, MASS

Name: ID of the center of masses. It should be larger than the total number of stars.

X,Y,Z: Position of center-of-masses respect to the center-of-mass of the cluster, in Parsec

VX, VY, VZ: Velocity of center-of-masses, in Km/s

KSTAR: Binary type 0 : Standard case.

-1 : Chaotic.

-2 : Continuous circularizing.

9 : Sequential circularization.

10 : Circularized.

11 : First Roche stage.

12 : End of first Roche stage.

13 : Start of second Roche stage.

xx : Further Roche stages.

ZLMSTY: Luminosity of the system  $L/L_{\odot}$

RADIUS:

MASS: total mass of the multiple system.

3) \*-bin (Binary) files contain 15 columns of Name, X, Y, Z, VX, VY, VZ, KSTAR, ZLMSTY, RADIUS, MASS, ASEMI, ESS, EBIN, P[d]

Name, X, Y, Z, VX, VY, VZ, KSTAR, ZLMSTY, RADIUS, MASS are the same as in \*-sin files.

ASEMI[pc]: Semi-major access (a) of the binary system in a unit of parsec

ESS: Eccentricity of the binary system

EBIN: Bounding energy of the binary system

P[d]: Period of the binary system in a unit of days

4) \*-higher (multiple systems) files contain 12 columns exactly like \*-all files but just for the higher-order (multiple) systems.

These four types of files are provided in all the time-steps. In our simulations we printed output in every 1 Myr, so there are 100 files covering 100 Myr of the evolution of the clusters. Please note that some clusters do not survive up to 100Myrs, because of their chosen initial conditions.

For each simulation there is a general output with the name [NAME]all.new There are 16 columns in this file:

Time, Trh, MTOT, Mbar, NTOT, Ncom, Nbin, Nbinhard, Nremnants, RH, Rcore, Vdis, Vmean, Rho-cen, Rneighbor, Nmultiples

Time: Evolutionary time indicating the age of the star cluster in Myr

Trh: Two body Relaxation time in Myr. It is calculated using Eq. 2, where N is a total number of stars and  $r_h$  is a half-mass radius of the cluster, and  $G$  is a gravity constant.

$$T_{rh} = 0.138 \frac{N}{\log(0.11N)} \sqrt{\frac{r_h^3}{G}} \quad (2)$$

MTOT: Total mass of the star cluster in a unit of  $M_\odot$

Mbar: Mean mass of the star cluster ( $\bar{m} = \frac{M_{TOT}}{N}$ ).

NTOT: Total number of stars

Ncom: Number of center-of-masses in the cluster, indication the total number of multiple systems.

Nbin: Total number of binary systems. Binary systems are defined as a systems with binding energy of Eq 3 and eccentricities (Eq 4) less than 1.

In these equation binary systems have masses  $m_1$  and  $m_2$  with relative distance and velocity of  $\vec{r}_{rel}$  and  $\vec{v}_{rel}$  and semi-major axis of  $a$ . The reduced mass of the system is  $\mu = \frac{m_1 m_2}{m_1 + m_2}$ .

$$E_{bin} = \frac{1}{2} \mu v_{rel}^2 - \frac{G m_1 m_2}{r_{rel}^2} = -\frac{G m_1 m_2}{2a} \quad (3)$$

$$e = \left[ \left(1 - \frac{r_{rel}}{a}\right)^2 + \frac{(\vec{r}_{rel} \cdot \vec{v}_{rel})^2}{a^2 G (m_1 + m_2)} \right]^{1/2} \quad (4)$$

Nbinhard: Total number of hard-binary systems. Hard-binaries are the systems with the binding energy larger than the total kinetic energy of the star cluster ( $|E_{bin}| > \frac{1}{2} \bar{m} \sigma^2$ , where  $\sigma$  is the velocity dispersion of the star cluster).

Nremnants: Number of the remnants in the clusters ( $KSTAR > 9$ ). Remnants can be a white dwarf (Helium, Carbon-Oxygen, Oxygen-Neon), neutron star, black hole or massless supernova remnant.

RH: is the half-mass radius of the star cluster in the unit of [pc].

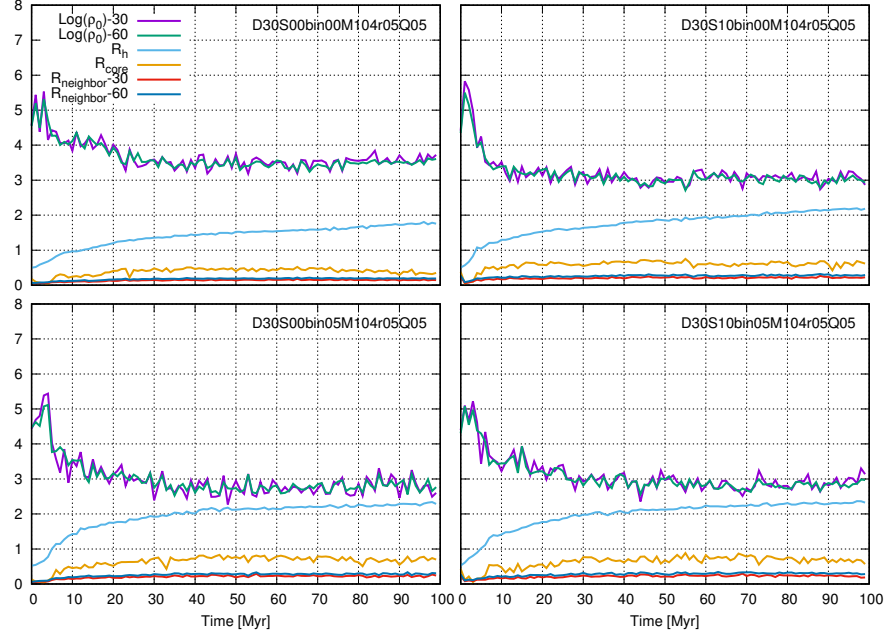


Figure 3: Evolution of half-mass radius (blue) and core radius (yellow), central density (violet for  $N_{neighbor} = 30$  and green for  $N_{neighbor} = 60$ ) of the clusters and the neighbor radii (red for  $N_{neighbor} = 30$  and dark-blue for  $N_{neighbor} = 60$ ) where the central densities are calculated ( $R_{neighbor}$ ). For simulation with initial total mass of  $10^4 M_{\odot}$  and half-mass radius of 0.5 pc in Virial equilibrium. Clusters in the top do not have any initial binaries and clusters in the bottom contain 50% initial binaries. Clusters in the right are initially segregated and the left ones are not segregated.

Rcore: is the core radius of the star cluster in the unit of [pc].

Vdis: is the velocity dispersion ( $\sigma = \sqrt{\frac{\sum(V-\bar{V})^2}{N}}$ ) of the star cluster in the unit of [km/s].

Vmean: is the mean velocity ( $\frac{\sum|V|}{N}$ ) of the stars in the unit of [km/s].

Rho-cen: is the central density of the star cluster calculated for  $N_{neighbor}$  (e.g. 30) stars in the center within the radius of  $R_{neighbor}$  (next column), equal to  $\frac{\sum_{i=0}^{N_{neighbor}} m_i}{\frac{4}{3}\pi R_{neighbor}^3}$  in the unit of [ $M_{\odot}/pc^3$ ]

Rneighbor: is the radius where central density(Rho-cen) is calculated.

Nmultiples: number of stars in the multiple systems (not binaries or single stars)

### 4.3 Example of outputs

As an example of the output of these simulations, we plotted the evolution of the basic properties of some star clusters, e.g. half-mass and core radius, total number and mass of the star clusters. Number of the binary systems and histogram of their orbital parameters (eccentricity, period, semi-major axis and mass ratio). In these examples we chose star clusters with the initial mass of  $10^4 M_{\odot}$  and half-mass radius of 0.5 pc in Virial equilibrium ( $Q=0.5$ ). The selected clusters are different in the initial degree of mass segregation, binary fraction and fractal dimension.



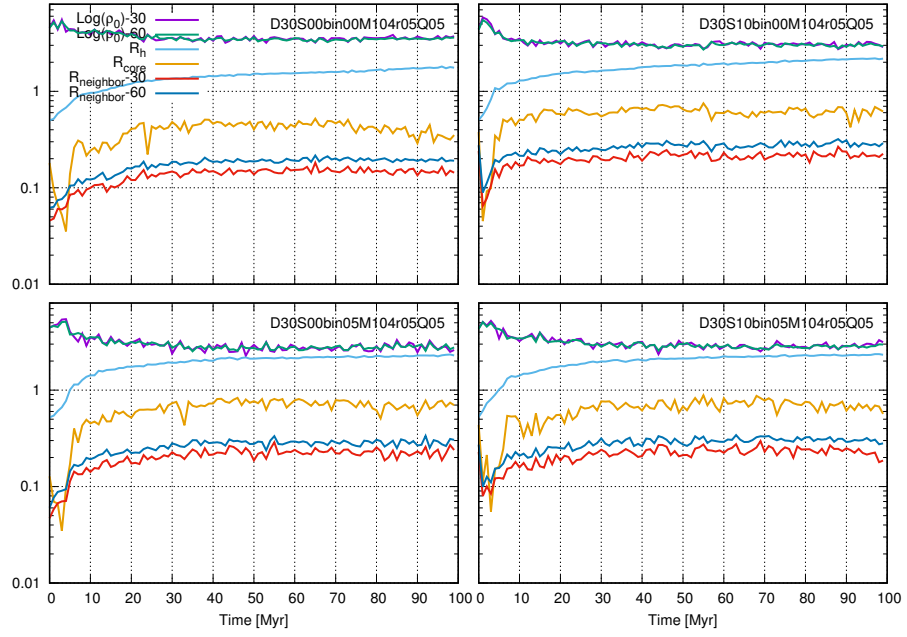


Figure 4: Same as Figure 3 but in logscale.

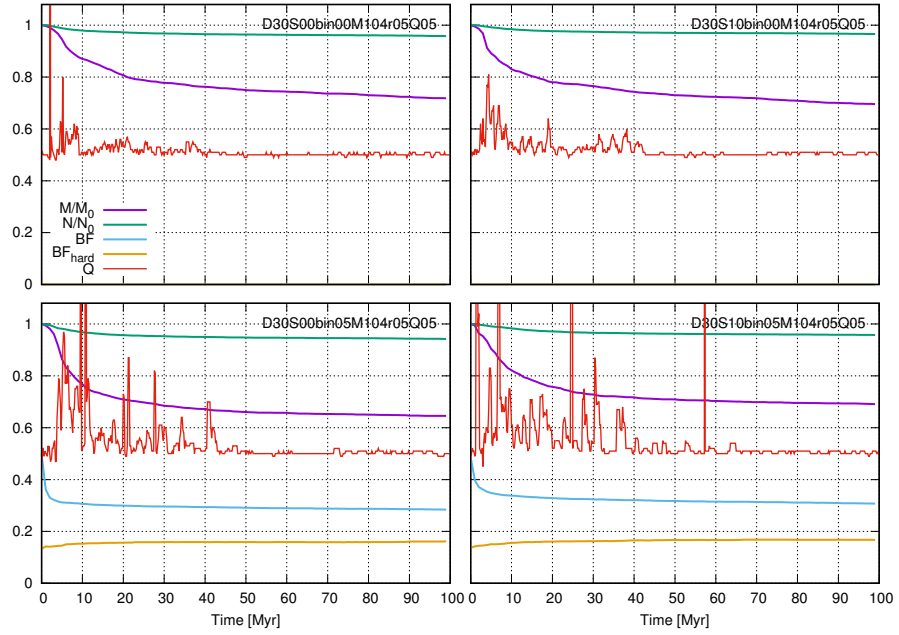


Figure 5: Evolution of the total mass (violet) and number of stars (green) within 100 Myr. These quantities are normalized to their initial values. Total number of binary system and hard-binaries are shown in blue and orange, respectively. The red line shows the evolution of Virial ratio ( $Q$ ) of the star cluster. For simulation with initial total mass of  $10^4 M_\odot$  and half-mass radius of 0.5pc in Virial equilibrium. Clusters in the top do not have any initial binaries and clusters in the bottom contain 50% initial binaries. Clusters in the right are initially segregated and the left ones are not segregated.

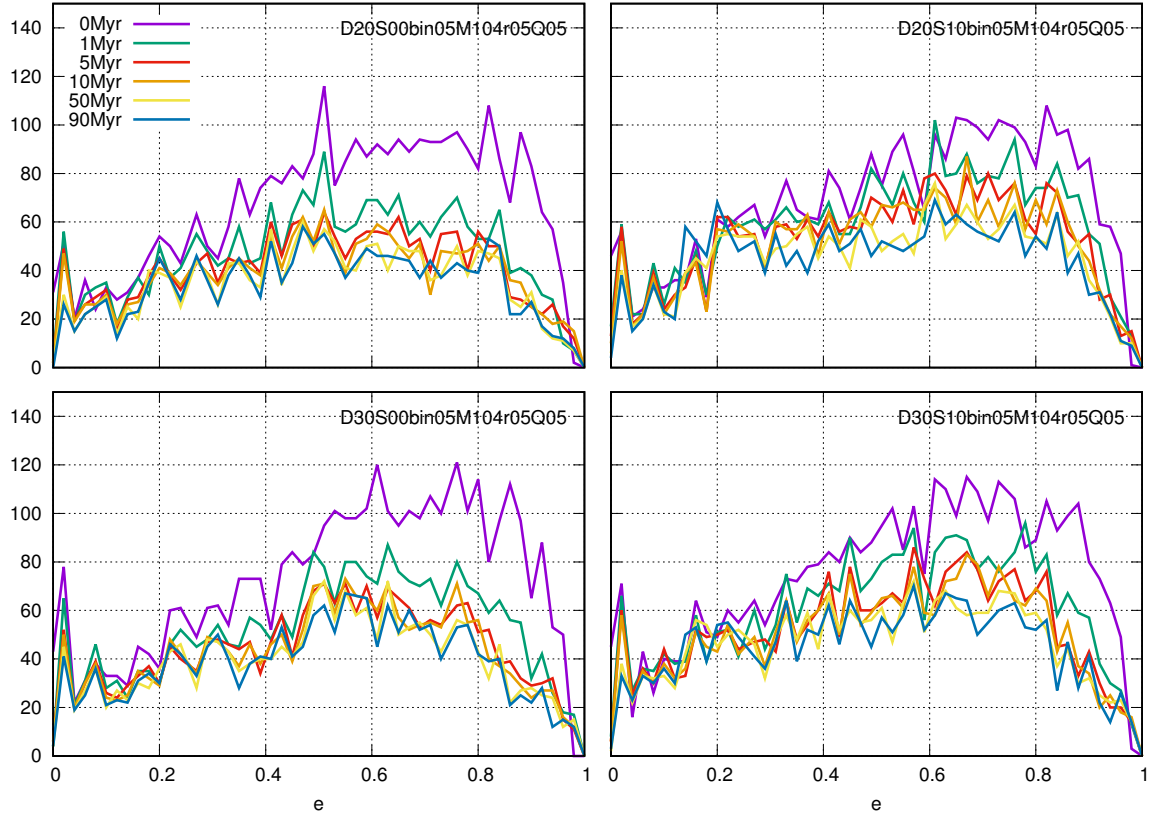


Figure 6: Histogram of the eccentricities of the binary systems at 0, 1, 5, 10, 50 and 90 Myrs, shown in violet, green, red, orange, yellow and blue respectively. For simulations with initial total mass of  $10^4 M_{\odot}$  and half-mass radius of 0.5pc in Virial equilibrium and 50% initial binaries. Clusters in the top are initially fractalize ( $D=2.0$ ) and clusters in the bottom are initially symmetric ( $D=3.0$ ). Clusters in the right are initially segregated and the left ones are not segregated.

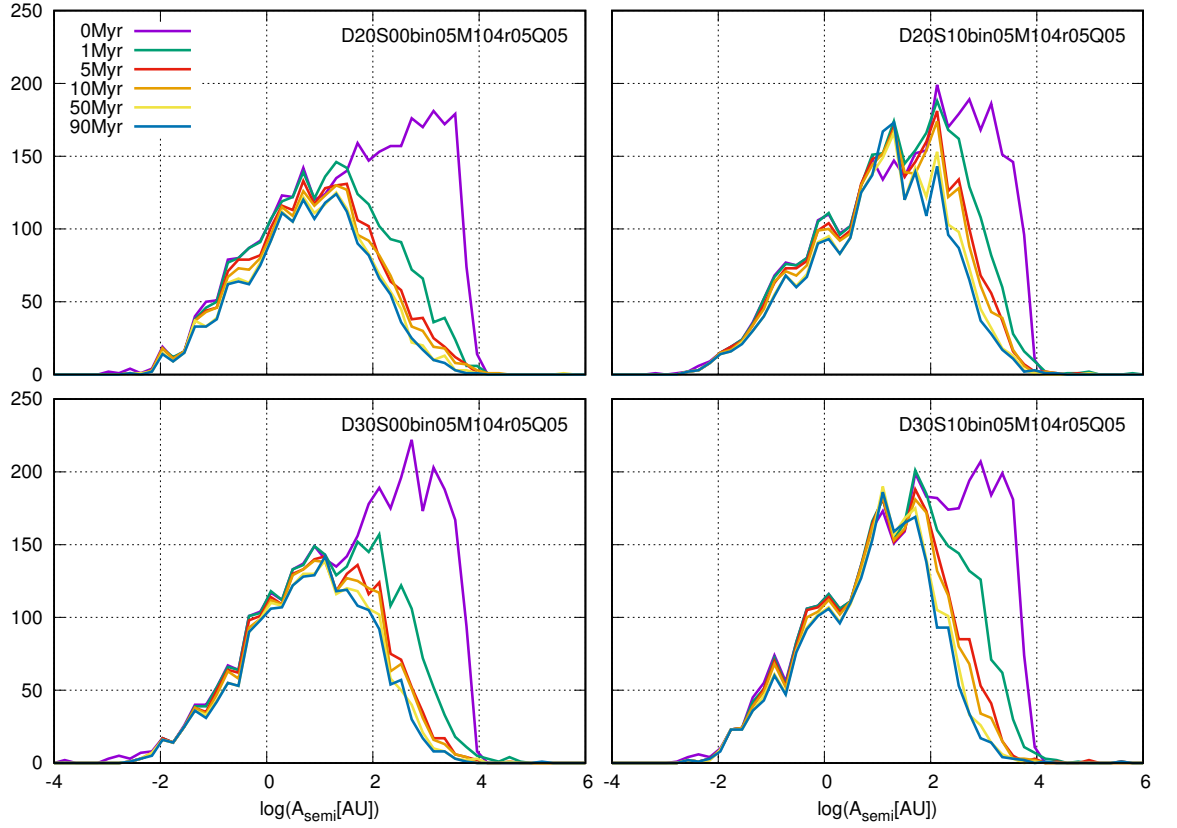


Figure 7: Histogram of the semi-major axis ( $a$ ) of the binary systems at 0, 1, 5, 10, 50 and 90 Myrs, shown in violet, green, red, orange, yellow and blue respectively. For simulations with initial total mass of  $10^4 M_\odot$  and half-mass radius of 0.5pc in Virial equilibrium and 50% initial binaries. Clusters in the top are initially fractalize ( $D=2.0$ ) and clusters in the bottom are initially symmetric ( $D=3.0$ ). Clusters in the right are initially segregated and the left ones are not segregated.

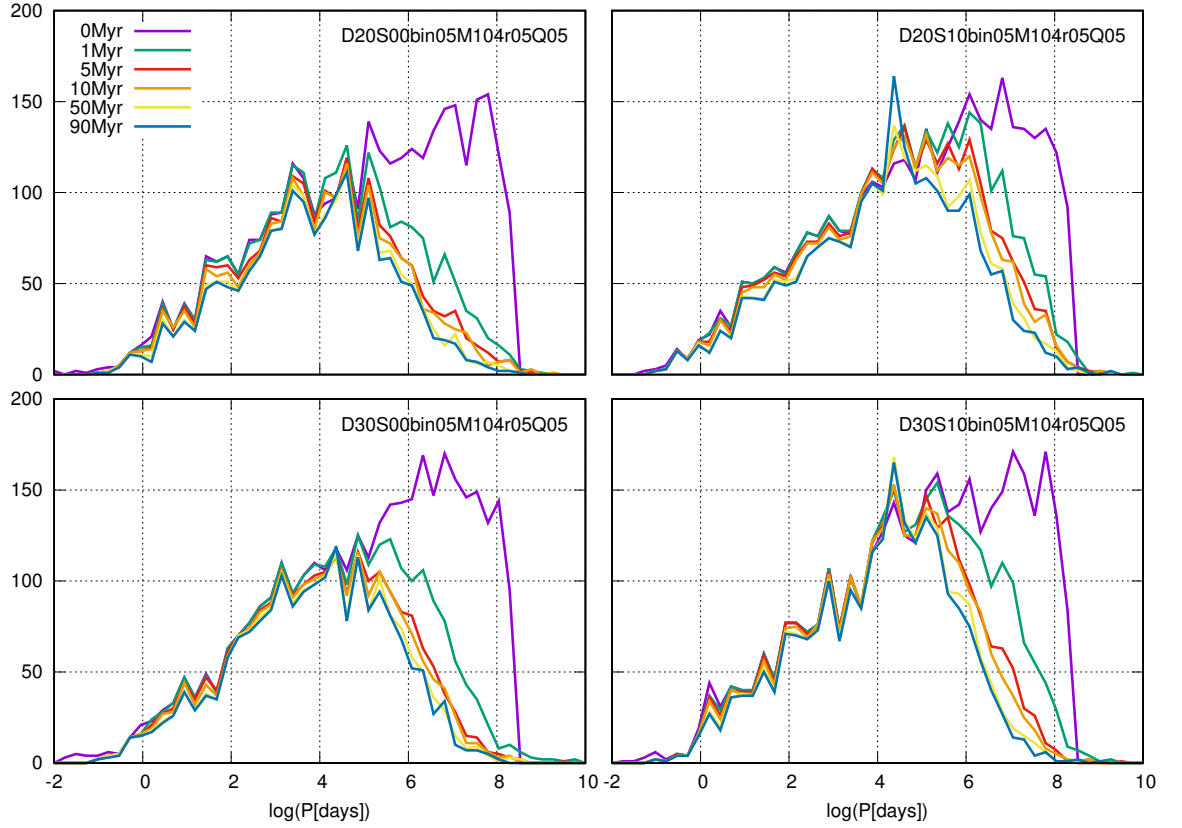


Figure 8: Histogram of the period ( $p$ ) of the binary systems at 0, 1, 5, 10, 50 and 90 Myrs, shown in violet, green, red, orange, yellow and blue respectively. For simulations with initial total mass of  $10^4 M_{\odot}$  and half-mass radius of 0.5pc in Virial equilibrium and 50% initial binaries. Clusters in the top are initially fractal ( $D=2.0$ ) and clusters in the bottom are initially symmetric ( $D=3.0$ ). Clusters in the right are initially segregated and the left ones are not segregated.

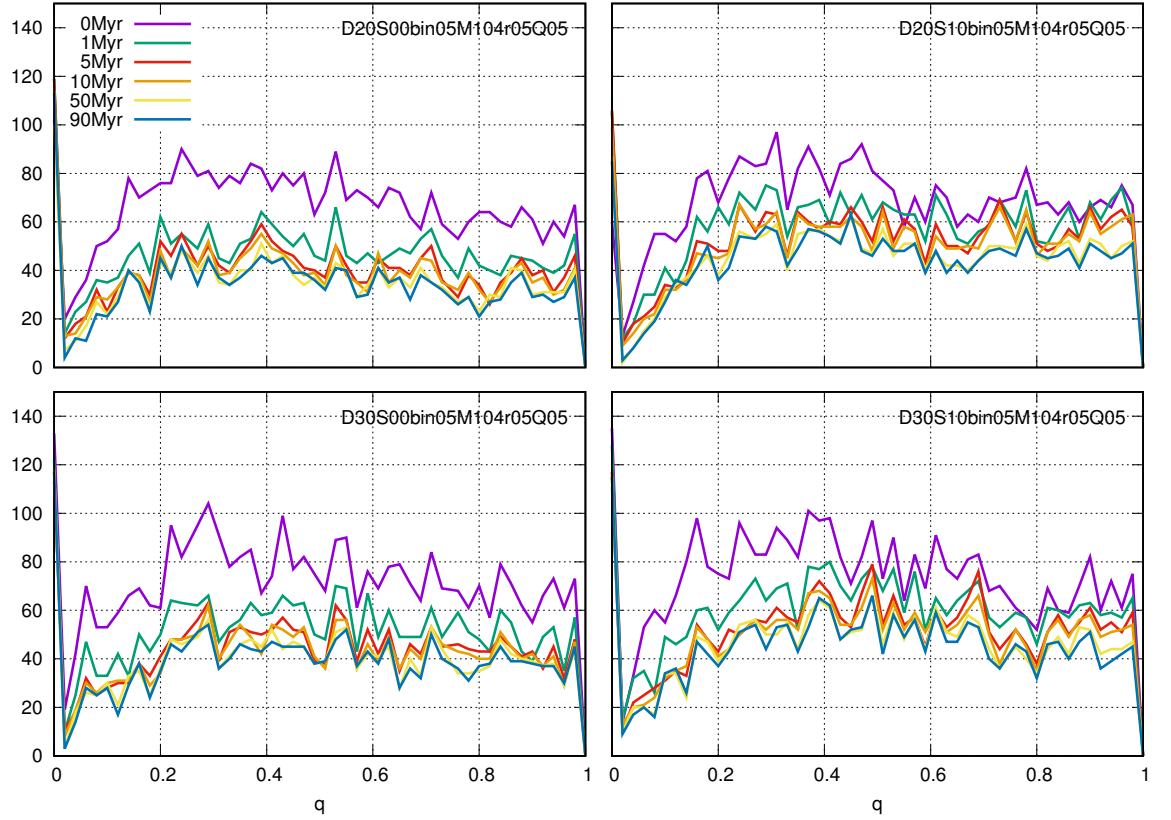


Figure 9: Histogram of the mass ratio of the binary systems ( $q = \frac{m_1}{m_2}$ ) at 0, 1, 5, 10, 50 and 90 Myrs, shown in violet, green, red, orange, yellow and blue respectively. For simulations with initial total mass of  $10^4 M_\odot$  and half-mass radius of 0.5pc in Virial equilibrium and 50% initial binaries. Clusters in the top are initially fractalize ( $D=2.0$ ) and clusters in the bottom are initially symmetric ( $D=3.0$ ). Clusters in the right are initially segregated and the left ones are not segregated.

## 5 Gaia simulation

Part of MYOSOTIS is a Gaia simulator, which is written in Python, aiming for simulating stars seen by Gaia G, GB (Gaia Blue) and GR (Gaia Red) filters (Figure 10 top). This code is available for public on Github (<https://github.com/zkhorrami/gaiaSimulations>). We have simulated 50 star clusters seen by Gaia (Buckner et al 2020, in prep). These simulations are being used as an input for INDICATE clustering tool. The clusters have 300 stars and located at the distance of 1kp. There are two sets of simulations available from these clusters: 1) Simulations using a constant extinction ( $A_V$  values) across the FOV (made by Gaia Simulator tool), and 2) Simulations using a variable extinction across the FOV, by locating each cluster at the center of a homogeneous SPH cloud (made by MYOSOTIS tool).

### 5.1 Constant $A_V$

We consider a constant value of  $A_V$  for each star in these clusters and their Gaia broadband G, GB (Blue), and GR (Red) are calculated using these  $A_V$  values. The constant  $A_V$  starts from 0.0 value upto 19.0 magnitude. In the output file for each cluster there are two sets of data file, one is *\*NAME\*G* and the other is *\*NAME\*GBR*. In each output file there are 24 columns: first four columns are, mass [ $M_\odot$ ], X [pc], Y[pc], Z[pc], and rest of the columns are the Gaia G magnitudes considering  $A_V$  value of 0.0, 1.0, 2.0, ..., 19.0

For the second sets of data, the order is exactly as the first, but instead of G magnitude, we calculated  $mag_{GB} - mag_{GR}$ . These extra outputs enables the user to plot color magnitude diagram for these clusters in different  $A_V$ s using three Gaia colors.

### 5.2 Variable $A_V$

For mentioned 50 star clusters, we used MYOSOTOS, in order to locate them in the center of the SPH homogeneous cloud, so that we can naturally produce a variable extinction across the FOV, since stars are located at different distances from the observer (3D). An example of variable extinction is shown in Figure 10 bottom.

The output for these simulations is a data file with the common format of MYOSOTIS (see section 3.2). We also provided the output image of each cluster in Gaia G band filter, in the fits format.

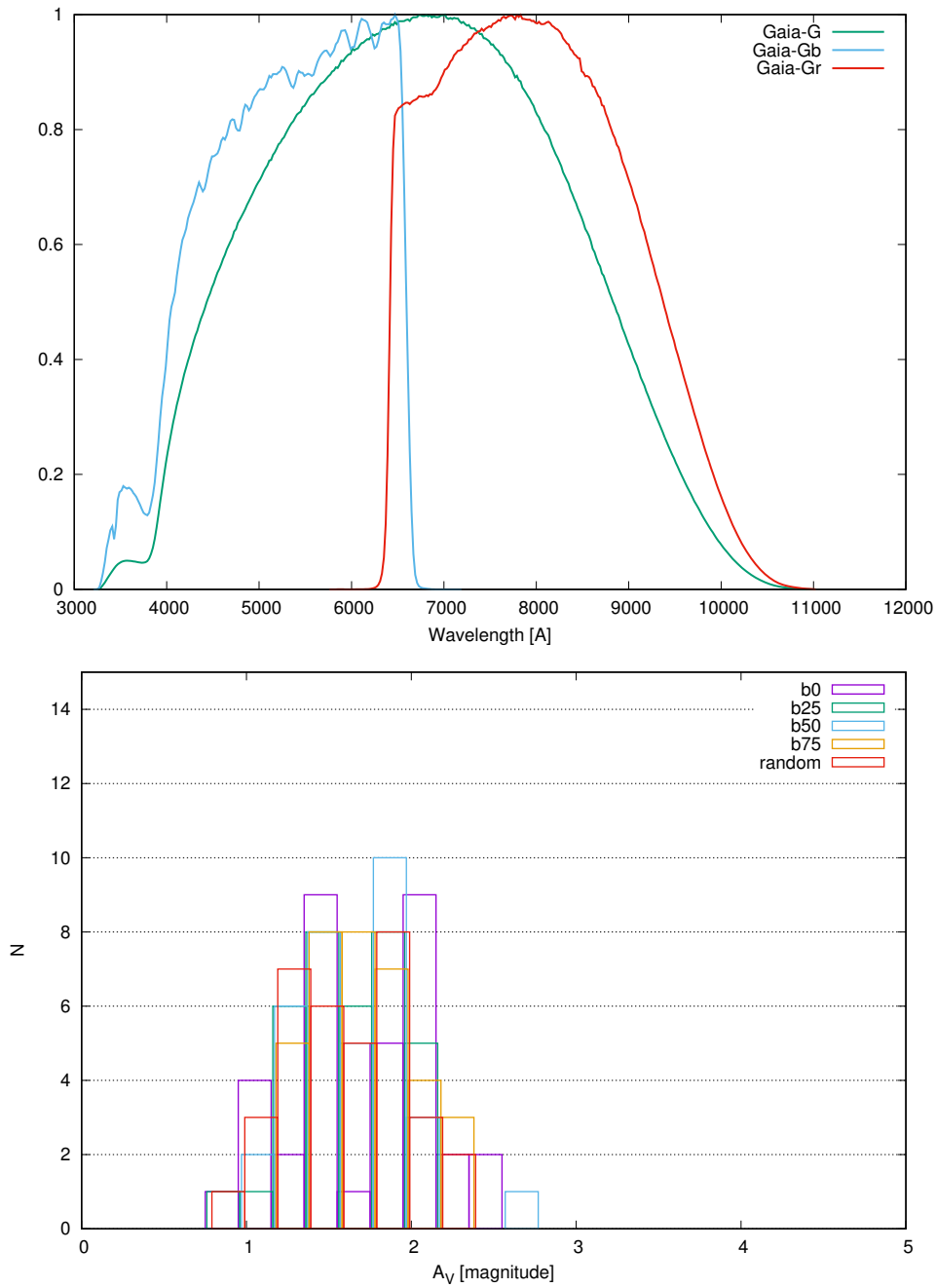


Figure 10: Top: Gaia broadband G, GB (blue), and GR (Red) filters. Bottom: Example of the histogram of variable  $A_V$  for five clusters using MYOSOTIS simulation of these clusters within a center of a homogeneous cloud. The variations are originated from the Z distance of stars in the cluster.