The Phantom of RAMSES user guide for galaxy simulations using Milgromian and Newtonian gravity

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Abstract:
This document describes the general process of setting up, running, and analysing disc galaxy simulations using the freely available program PHANTOM OF RAMSES (POR). This implements Milgromian Dynamics (MOND) with a patch to the RAMSES grid-based N-body and hydrodynamical code that uses adaptive mesh refinement. We discuss the procedure of setting up isolated and interacting disc galaxy initial conditions for POR, running the simulations, and analysing the results. This manual also concisely documents all previously developed MOND simulation codes and the results obtained with them.

1. Introduction
Milgromian Dynamics (MOND) is an extension of Newtonian dynamics to encompass the observed dynamics in the Solar System as well as in galaxies without postulating invisible haloes around them [1]. MOND computes the gravitational potential of galaxies using only the distribution of baryons. It has been very successful in this regard, especially because it predicted some very tight scaling relations which were subsequently observed [2, 3]. These are a consequence of Milgrom’s formula
\[ g = \sqrt{g_N a_0} \quad \text{for} \quad g_N \ll a_0 = 1.2 \times 10^{-10} \text{ m s}^{-2}, \]  
where \( a_0 \) is Milgrom’s constant, \( g \) is the strength of the true gravity, and \( g_N \) is that of the Newtonian gravity. To achieve a generalization of gravity applicable in non-spherical systems, MOND requires a generalized Poisson equation derived from a Lagrangian. Two classical variants have been proposed, one with an quadratic Lagrangian [AQUAL; 4], and one with a Lagrangian making use of an auxiliary field, which is called the quasi-linear formulation of MOND [QUaMOND; 5]. MOND may be a consequence of the quantum vacuum [6–9]. Reviews of MOND can be found in [2, 10].

PHANTOM OF RAMSES [POR; 11] is a numerical implementation of QUaMOND, whose field equation for the potential \( \Phi \) is
\[ \nabla^2 \Phi \equiv -\nabla \cdot g = -\nabla \cdot (\nu g_N), \]  
where \( \nu \) is the MOND interpolating function with argument \( y \equiv g_N/a_0 \), with \( g \) and \( g_N \) being the true and Newtonian gravitational acceleration vectors, respectively, and \( \nu \equiv |\nu| \) for any vector \( \nu \). The current version of POR uses the simple form of the interpolating function (e.g. equation 5 of [12])
\[ \nu(y) = \frac{1}{2} + \sqrt{\frac{1}{4} + \frac{1}{y}}. \]  
\( g_N \) is found from the baryonic density \( \rho_b \) using the standard Poisson equation
\[ \nabla \cdot g_N = -4\pi G \rho_b. \]  
The boundary condition for the MOND potential far from an isolated matter distribution is
\[ \Phi = \sqrt{GM a_0} \ln R, \]  
where \( M \) is the mass within the simulation box, and \( R \) is the distance from its barycentre in the simulation unit of length.

A handful of Milgromian N-body codes were developed before POR to handle MOND computations, and these have been applied to various problems. The first multi-grid, Milgromian N-body code was developed by [13] to investigate the stability of disc galaxies. This was later extended to simulate how they might warp due to the external field effect [EFE; 14]. Another N-body solver which implemented the AQUAL formulation of MOND was developed and used to study the evolution of spiral galaxies using pure stellar discs [15]. Gas dynamics was later included
using a sticky particle scheme at low resolution [16]. N-MODY was developed to solve the Milgromian Poisson equation in spherical coordinates [17] and used to investigate dynamical friction [18], orbit instabilities [19], and stellar kinematics [20–22]. Milgromian N-body codes tailored to cosmological simulations have also been developed [23–26]. Another N-body solver called RAYMOND [27] was developed to implement both the AQUAL [4] and QUMOND [5] formulations of MOND. RAYMOND has been applied to cosmological [28], galaxy cluster [29], and other problems. However, not all the aforementioned N-body codes can be applied to generic scenarios simultaneously involving particles, gas dynamics, and star formation.

The FORTRAN-based POR code was developed by Fabian Lüghausen [11]. It is a customized version of RAMSES [30], which exclusively uses Newtonian dynamics to compute gravity. POR can compute gravity using MOND by numerically solving Equation 2. Since POR is a patch to RAMSES, it inherits use of the adaptive mesh refinement (AMR) technique. POR is equipped to handle particles, gas dynamics, and star formation, and can be applied to diverse problems. It allows the user to compute gravity in both Milgromian and Newtonian frameworks [11].

This document serves as a tutorial/manual for the general use of POR, with some suggestions for the specific case of setting up and simulating a disc galaxy. Most of the steps and parameters described here are specific to POR, except the installation of RAMSES. For a detailed description of individual parameters, it is always recommended to read the RAMSES manual\(^2\). Most of the parameters and files described here can be edited safely without disturbing the core algorithms. Before changing parameters or files that are not mentioned here, it is important to fully understand the workings and consequences of the change.

In Section 2, we explain the installation procedure of RAMSES and POR. In Section 3, we explain how to set up MOND disc templates using Disk Initial Conditions Environment (DICE), and thereby generate rotating disc initial conditions for POR. In Section 4, we describe the workings of POR, focusing on particle-only and hydrodynamical runs with and without star formation. In Section 5, random turbulence generation is briefly discussed. Section 6 discusses the extractpor tool used to analyse particle data in RAMSES simulation outputs. In Section 7, we mention all publications based on POR. We conclude in Section 8.

### 2. Installation and setup of the code

The POR patch by Fabian Lüghausen is rated to work with the 2015 version of RAMSES, which has since been modified (the latest RAMSES version is available here \(^3\)). Later versions are not compatible with POR. It is therefore recommended to use the 2015 version of RAMSES with POR. The jointly tested version of RAMSES and POR is available here \(^3\), in the PoRhydro folder.

The following steps describe the installation and compilation of RAMSES and POR. These procedures are adapted from the RAMSES manual, where they are described further:

1. The main folder needed for compilation of RAMSES is bin.

In the bin folder, there is a makefile. Now, do:

```
$ cd ~/PorR_hydro/ramses/bin/
```

2. In the makefile, certain flags need to be changed. Makefile:

| Compilation time parameters |
|-----------------------------|
| NVECTOR = 32                |
| NDIM = 3                    |
| NPRE = 8                    |
| NVAR = 6                    |
| NENER = 0                  |
| SOLVER = hydro              |
| #PATCH = ../patch/phantom    |
| #PATCH = ../patch/phantom_statparts (particle-only run) |
| #PATCH = ../patch/hydro/phantom_merge |
| PATCH = ../patch/hydro/phantom_extfield (hydro run) |
| EXEC = RAMSES               |

3. All these flags are explained in the RAMSES manual\(^2\). F90 and FFLAGS should be set carefully.

```
F90 = mpii90 -record-marker=4 -O3 -ffree-line-length-none -g -fbacktrace
FFLAGS = -x f95-cpp-input $(DEFINES)$
```

4. F90 sets the Fortran compiler and FFLAGS is used to specify the required MPI libraries, which are mainly used for parallel computing. This is important given the likely high computational cost. The default makefile\(^3\) uses the above-mentioned F90 and FFLAGS. If one’s computer is not compatible with these default parameters, they can be changed in the makefile.

5. Once all the required flags are set, compile the code:

```
$ make
```

After compilation, one can test the installation as described in section 2.3 of the RAMSES manual\(^2\).

6. To make the files again, go to the bin folder and execute:

```
$ make clean
$ make
```

The RAMSES manual was written in 2002 and has not been updated since, so there might be subsequent modifications to the parameter file. One must use the phantom patch to do simulations in MOND. For Newtonian simulations, it is recommended to use this patch and set the mond flag to .false. in the namelist.

### 2.1. Compilation of the code with the POR patch

We now describe the procedure to link the POR patch and recompile RAMSES. To activate the POR patch, the following parameters must be specified in the makefile (# means a comment):

\(^2\)https://bitbucket.org/rteyssie/ramses/src/master/
\(^3\)https://bitbucket.org/SrikanthTN/bonnpor/src/master/
By default, RAMSES uses periodic boundary conditions, but the \texttt{POR} patch in\textsuperscript{3} specifies and uses different boundary conditions appropriate to isolated galaxy simulations. The 2015 version of RAMSES available in\textsuperscript{3} contains a staticpart patch and a hydrodynamical patch with compulsory additional merger and EFE patches whose effects can be disabled (Section 4.2). These patches are task-specific customizations of \texttt{POR}. For a particle run, \texttt{phantom\_staticparts} can be used while for a hydrodynamical run, \texttt{phantom\_extfield} can be used. Only one patch can be used at a time. One must change the path to the user’s directory before making the file. After specifying the parameters, make the file again.

\section{Disk Initial Conditions Environment (DICE)}

Any galaxy or cosmological simulation needs initial conditions. The RAMSES user guide refers to two websites for these, but they are for cosmological runs. The MUSIC\textsuperscript{4} code also provides initial conditions for the latter, and is recommended. The setup of cosmological MOND simulations will be discussed elsewhere. This guide focuses on galaxy simulations, for which we generate initial conditions with an adapted version of Disk Initial Conditions Environment \cite{DICE}. The original version of DICE can be found here\textsuperscript{3}. It is not compatible with MOND or the 2015 version of RAMSES\textsuperscript{3}, so we used a modified version of DICE available here\textsuperscript{3}. This has two versions, one for particle-only runs (the \texttt{dicer\_particle} folder, hereafter P-DICE) and the other for hydrodynamical runs (in \texttt{dicer\_gas}, hereafter H-DICE). These algorithms were developed by Graeme Candlish, Roy Truelove, Indranil Banik, and Ingo Thies. Both are equipped to initialize dic galaxies in MOND, but in principle other methods could be used and advanced with the POR patch. Before installing DICE, \texttt{CMake}, \texttt{GSL}, and \texttt{FFTW} must be installed. If this is not already the case, installation instructions are provided here\textsuperscript{3}.

\subsection{Installation and setup}

As mentioned above, the folders \texttt{dicer\_particle} and \texttt{dicer\_gas} contain P-DICE and H-DICE, respectively. Extract them to \texttt{/local} in one’s home directory. In \texttt{dicer\_particle}, the \texttt{disc} folder is required for disc galaxy simulations. Now, in \texttt{disc}, the \texttt{bin} folder contains the \texttt{makefile} needed for compilation, while the \texttt{example} folder contains the parameter files. To compile P-DICE, execute:

\begin{verbatim}
$ cd dicer\_particle
$ cd disc
$ mkdir build
$ cd build
$ cmake ..
$ make
$ make install
\end{verbatim}

To compile H-DICE, execute:

\begin{verbatim}
$ cd dicer\_gas
$ mkdir build
$ cd build
$ cmake ..
$ make
$ make install
\end{verbatim}

H-DICE does not contain an additional disc folder like P-DICE.

\subsection{Running DICE}

The \texttt{dicer\_gas} and disc (in \texttt{dicer\_particle}) folders contain four sub-folders:

1. \texttt{cmake} should not be altered,
2. \texttt{build} will contain the executable,
3. \texttt{src} contains the source files which encode the physics required for computation, and
4. \texttt{example} contains files required to generate the initial conditions, with task-specific configuration files like M31, M33, and generic scenarios like a disc galaxy, disc with a bulge etc. Only the Milky Way (MW), M31, and M33 cases are rated to work.

We used the \texttt{test\_mw\_config} configuration file for our disc galaxy:

\begin{verbatim}
Redshift 3.0
Galaxy .\.example/params\_files/testMilkyWay.params
Filename dice\_highz
ICformat Gadget2
Nthreads 32
\end{verbatim}

In the .\texttt{config} file, specify the path to the parameter file. The redshift is unused in our MONDified DICE. The testMilkyWay.params is the parameter file used, though other params files exist in the .\texttt{example/params\_files} folder. Custom templates can be created using these parameter files, though only the MW, M31, and M33 cases are rated to work. There are mainly three types of parameters in testMilkyWay: \texttt{global parameters}, \texttt{outer disc}, and \texttt{inner disc}. For both P-DICE and H-DICE, once the parameter file is set, go one directory up and execute:

\begin{verbatim}
$ cd bin
$ ./dicer ..\example\test\_mw\_config
\end{verbatim}

After execution, 2 output files named Milky\_Way\_output\_p2\_k0.txt and Milky\_Way\_rotation\_curve.txt will be created in the \texttt{bin} folder. The rotation curve is only required for hydrodynamical simulations.

\footnotesize
\textsuperscript{3}https://bitbucket.org/ohahn/music/src/master/
\textsuperscript{4}https://bitbucket.org/vperret/dice/src/master/
4. Running POR

After compilation of RAMSES with the required POR patch, one can customize the namelist file available in the PoR_namelist folder to meet a scientific goal. PoR_namelist consists of all the namelist files we have used for our runs. PoR.nml is a general template which can be customized. PoR-static.nml is the file we used for our particle-only run, while Test_hydro_nw_NSFR.nml was used for the hydrodynamical run without star formation. There is a general namelist folder which consists of .nml files that can be used to test e.g. the installation of RAMSES.

4.1. Particle-only run (staticpart patch)

Use the /patch/phantom_staticparts patch and PoR-static.nml, take care on the boundary conditions:

```
&RUN_PARAMS
poisson=.true.
pic=.true.
mond=.true. – Activates MOND poisson solver
nrestart=0 – used to restart a run from any output
/

&AMR_PARAMS
levelmin=7
levelmax=12
ngridmax=2000000
boxlen=1024.0
npartmax=2000000/

ngridmax and npartmax should be of order 10^6 to avoid memory errors.

&OUTPUT_PARAMS
foutput=8000 – Frequency of outputs in terms of coarse steps
noutput=100 – Number of outputs to be generated
delta_tout=100. – Interval of the output in Myr
tend=10000. – Simulation end time, in this case 10 Gyr
/

&INIT_PARAMS
filetype=‘ascii’
initfile=../path/to/Milky_Way_output_p2_0.txt as the input.
/

&POISSON_PARAMS
a0_ms2=1.2e-10
m_threshold=1.e+30 – critical part, set it based on usage
gravity_type=0
cg_levelmin=999
/

&BOUNDARY_PARAMS
nboundary=6
ibound_min=-1, 1, 0, 0, 0, 0,
ibound_max=-1, 1, 0, 0, 0, 0,
jboun_min=0, 0,-1, 1, 0, 0,
jboun_max=0, 0,-1, 1, 0, 0,
```

There are some parameters which are mandatory in all runs, such as &Run_Params, &AMR_Params, &Output_Params, &Init_Params. Others vary based on specific requirements. Most of these parameters are detailed in the RAMSES manual, so we only stress those specific to POR. Parameters not shown here should not be changed unless required.

The staticpart patch integrates particles below a certain mass \( m_{\text{threshold}} \), while more massive particles are kept static but are considered when evaluating \( g_N \) in Equation 4. This method is an effective way to save computation time. If one wants to evolve all the stellar particles in a particle-only simulation, then \( m_{\text{threshold}} \) should be set to a suitably large value, e.g. \( 10^{30} M_\odot \). The units from the DICE output are the same as required by POR for input (i.e. \( M_\odot \), kpc, and km/s), while units.f90 has the units used by PORT in which \( G = 1 \).

One can modify &Output_Params and &AMR_Params, but it is not recommend to tamper with other blocks. In the above example, the Milky_Way_output_p2_0.txt obtained from P-DICE is given as the input file, with the rotation curve unused. Once all parameters are set in the namelist file, the simulation can be started by executing:

```
$ mpiexec -n 32 . . /ramses3d . . / filename.nml
```

This calls the simulation to run on 32 CPUs using parallel computing (the number can be changed). Regardless of the directory of execution, one must specify full paths to the ramses3d and namelist files. To run these simulations without parallel computing, simply execute:

```
$ . . /bin/ramses3d . . / filename.nml
```

Users should check the computing capacity before running simulations without parallel computing.

After starting the simulation, it might terminate with error message - “SEGSEV - invalid memory reference”. This is a memory error, which can be solved by increasing npartmax up to \( 10^7 \) and ngridmax up to \( 8 \times 10^6 \) (the codes are not rated for larger values). The npartmax variable must be at least equal to the number of particles in the DICE template. Turning off the movie may help. CPU and memory errors are a bit alarming, but are easily overcome and should not be a big concern for beginners.

The simulation will produce output folders for each snapshot. During the run, if the memory allocated is too small, the simulation will stop and ask to increase the number of grid cells. One must then go back to the namelist file and increase ngridmax or npartmax based on what is asked. The restart protocol is rated to work, so restart the run from the last output file by setting nrestart to the desired output number (the default of 0 means to start from scratch). If the run stops before finalising output_45, set nrestart = 45 and resume the run by executing the above-mentioned command.
4.2. Hydrodynamical run without star formation

We performed this run with the /patch/hydro/phantom_extfield patch, which is a modification to POR. The EFE and merger scenarios are included using the MOND Poisson solver, but both features can be turned off.

4.2.1. DICE with gas component

DICE is again used to set up the initial conditions. Since the gas component is included, we used H-DICE in the dice_gas folder. To include a gas component, the test_MilkyWay.params was slightly modified:

```
# Global parameters
# Virial velocity of the galaxy [km/s]
v200 = 200.0
# Virial mass of the galaxy [1e10 Msun]
m200 = 9.15#8.4 old
Gas_fraction = 0.2
GasT = 50000.0
```

The highlighted lines are the new additions to the H-DICE template. These lines specify the gas component parameters. The gas fraction depends on the galaxy, here 20% gas fraction was used for the MW. The gas temperature should be set equal to another parameter called T2, which is present in the namelist file of POR. One must be careful that the gas fraction should be greater than the mass fraction of the outer component, in this particular case, more than 18%. This is because the distribution of gas in H-DICE is done in a particular way, so one should be cautious while setting the gas fraction [32]. The template has a default mass fraction of 17.64% for the outer disc component, with the remaining 82.36% for the inner disc [33]. This version is only rated for two exponential disc components. For a beginner, it is recommended to take advice at this point before proceeding further.

H-DICE can be started the same way as P-DICE. After starting the DICE run, one might notice a message in the terminal “Gas is too cold to satisfy the Toomre condition everywhere. Increase T by a factor of . . .”, and/or “WARNING: only writing data for component 1”. The first message is just a warning about the global disc stability, and has no impact on the results — it can be ignored. Temperature here is used as a measure of velocity dispersion including turbulence, so it is not the true gas temperature. The second message can also be ignored — it indicates that the second component defined in DICE is treated as stars and used for calculating the potential, but not printed in the output as the gas will be added in POR [32]. The particle data written to the disc template file contains only the stellar component.

The rotation curve file has columns for the gas disc scale height and its radial gradient. This is critical as the gas component is created in POR itself (in the merger and extfield patch) by reading in the gas data from the rotation curve file and some parameters to be set in the namelist file, e.g. gas mass and temperature. Care is needed to ensure compatibility of the parameters used for DICE and POR.

4.2.2. POR with merger and external field patch

In the hydrodynamical case, we did not explicitly set up an isolated disc galaxy, but instead adapted the merger template condinit. This sets up two disc galaxies in the simulation box, so we switched off the second galaxy by setting its mass and velocity to zero and placing it outside the simulation box. The namelist file for each run should be customized as required, we show part of Test_hydro_mw_NSFR.nml as an example:

```
&RUN_PARAMS
mond = true.
Activate_g_ext = false.

&INIT_PARAMS
filetype = ‘ascii’
initfile(1) = ’path/to/the/DICE/output/’

&MERGER_PARAMS
rad_profile = ’double_exp’
z_profile = ’sech_sq’
Mgas_d1 = 45.75
Mgas_d2 = 0
IG_density_factor = 1.0e-2
T2 = 40.0
scale_s2 = 1.
Vcirc_d1 = ”Milky_Way_rotation_curve.txt”
Vcirc_d2 = ”Milky_Way_rotation_curve.txt”
IC_part_file_gal1 = ”Milky_Way_output.p2_k0.txt”
IC_part_file_gal2 = ”Milky_Way_output.p2_k0.txt”
gal_center1 = 0.,0.,0.
gal_center2 = 2000,0.,0.
Vgal1 = 0.,0.,0.
Vgal2 = 0.,0.,0.
```

The namelist has other parameters, but we show only those critical to the simulation. If one were to use a similar setup, the following suggestions are helpful:

1. In the RAMSES makefile, one must provide the path to the external field patch and recompile RAMSES.
2. The POR patch can accommodate both MOND and Newtonian physics. The latter is used if one sets `mond = false` allowing simulations with both gravity theories using POR.
3. Setting `Activate_g_ext = false` turns the EFE off. Hydrodynamical simulations with the EFE are discussed further in [32].
4. For the `initfile(1)`, one must give the path to the directory where `Milky_Way_output.p2_k0.txt` and `Milky_Way_rotation_curve.txt` are present. These files

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6http://www.physics.usyd.edu.au/~tepper/codes/ramses/trunk/doc/html/patch_2hydro_2merger_2condinit_8f90_source.html

Phantom of RAMSES user manual
should be specified for ic_part_file_gal1 and Vcirc_dat_file1, respectively. The same path and files can be given for the second galaxy, which is unused here.

5. The main things that need attention are the &Merger_Parms. The gas mass of the galaxy is in units of $10^9 \, M_{\odot}$. If simulating interacting galaxies, they should not start too close together. We switched the second galaxy off by setting its gas mass and velocity to 0 and placing it outside the box, e.g. box size = 500 kpc, gal_center2 = (2000, 0, 0) kpc. The first galaxy was placed at the box centre.

6. For isolated simulations, both galaxies should have zero initial velocity, i.e. Vgal1 and Vgal2 should be zero. gal_axis defines the disc’s spin axis. For standard isolated simulations, use (0, 0, 1) for counter-clockwise rotation around the z-axis, or (0, 0, −1) for clockwise.

7. The $T2_{ISM}$ parameter in the namelist and Gas_T in the H-DICE template should be equal. The temperature floor $T2_{star}$ should be set to a slightly lower value than $T2_{ISM}$. We used $T2_{ISM} = 40,000$ K and $T2_{Star} = 30,000$ K. The simulation is not rated to work with $T2_{ISM}$ or $T2_{Star}$ below 25,000 K.

After taking care of all these parameters, one can start the run, leading to creation of the output folders in due course. The simulations are RAM and memory intensive — a hydrodynamical disc galaxy advanced for 1.5 Gyr on a 4-core laptop could take a week or two depending on the RAM and might occupy up to 100 GB of hard disk space. These estimates would vary depending on the parameters and machine used — see section 4.2 of the RAMSES manual for more details.

4.3. Hydrodynamical run with star formation

Converting gas into stars requires careful treatment of baryons, for which RAMSES is well equipped and tested [34]. Since POR is just a modification to the Poisson solver, it does not affect the baryon treatment, inheriting that of standard RAMSES.

To activate star formation, one has to include the &Physics_Parms in the namelist file. One can add &Physics_Parms to the Test_hydro_mw_NSFR.nml and activate star formation. Alternatively, one can use the MW_hydro_SFR.nml provided in, which we used for our star formation run.

### 5. Random turbulence generation

To allow for initial turbulence and (optionally) density fluctuations, a random perturbation algorithm has been included based on the square-square subdivision [35]. It is similar to the well-known diamond-square algorithm widely used for the generation of random terrains, but provides a higher quality of randomness and fewer artefacts. The algorithm first applies random perturbations on a $2 \times 2 \times 2$ cubic array. At each subsequent step, the cube cells are subdivided into $2 \times 2 \times 2$ arrays and perturbed again, while the magnitude of the perturbation is reduced by a factor of 2 (unless the user chooses a different value). Additional factors can be applied to the magnitude of each step, following a user-defined power spectrum. The resulting random noise is then multiplied with the density and/or the three velocity components to get turbulence.

The algorithm requires some additional variables to be set in the &Merger_Parms in the namelist file, and an extra parameter file qqm3d.par. The extra lines in the namelist are:

```
&MERGER_PARMS
...!
flg_qqm3d=-1 !Master switch (-1 means off)
devflat_dens=1.0 !density mean unperturbed level
devscal_dens=0.1 !density deviation scale
devflat_vel=1.0 !same, for velocities
devscal_vel=0.1
scale_objsize=1.0 !size of the perturbation mask
```

The master switch controls the overall usage of the random perturbation algorithm. “-1” means “off”, other modes are:

- 0 or 10: only density is perturbed,
- 1: only adds absolute perturbation to velocities,
- 2: combines modes 0 and 1,
- 11 and 12: like 1 and 2, but with velocity perturbations scaled by the circular velocity (recommended),
- 21 and 22: like 1 and 2, but with velocity perturbation relative to actual velocities (experimental).

The parameter file qqm3d.par contains:

```
**** Setup parameters for qqm4rams ****
8 2.5 4. 1 nsize,fsize,scalh ini,balance values
1 1 1. init mode, deviate (0:lin, 1:Gauss), power
0.0 initial corner master values
10 0 1.0 1.0 hr_mode, stop rnd h after n iter (<= 0:off), hreduce iter factor+power
309562 -1 seed, seed initialization mode
— Corner perturbation scaling —
0.2 scalh00
— Feature power spectrum —
0.1 scalh01
— Corner initial values —
0. x01
```

All the above parameters are described in the RAMSES manual. The $t_{star}$ parameter is the star formation timescale in Gyr. Setting it to a finite, non-zero value activates star formation. One can add other parameters as per requirements.
Only the lines most relevant for beginners are shown. Other lines are mostly experimental and should be left as they are, unless the user looks at the source code for more details about their purpose. The most relevant values for hr_mode are:

- 4: uses the lines from the power spectrum block as weightings. The magnitude of the first non-zero perturbation is equal to \( \text{devscal} \) and will be reduced by \( \text{hreduce} \) (typically \( \frac{1}{2} \)) for each refinement level.
- 10: uses a flat power spectrum with starting level \( f\text{size} \). Non-integer values are used via an interpolation scheme.

The other hr_modes should not be used for scientific runs. For details, see the source file \( qqm4ramses.f90 \) and its subroutine \( \text{init}_qqm3d \).

6. Extraction of data with extract\_por

For the extraction of particle data, a tool called extract\_por was developed by Ingo Thies and used here. Now including additional features related to star formation, extract\_por\_sfr is available here\(^3\). This is a user-friendly tool that does not require much time to learn. After the tool is downloaded, it can be extracted to \(/\text{home/local} \). Installation is done by executing:

\[
\text{$ make \ x\ p o r\ d a t a $}
\]

Inside extract\_por, fmtRAMSES.par is the parameter file where the extraction parameters can be set. It contains:

```
"path/to/your/outputfiles"
38 Output No.
32 Number of CPU threads
0 COM reset

— RADIAL BINNING SECTION ——
10. 500 binning radius (in system units), nbins

— Image params ——
1 1 0 flgimage
250 250 imagecenter
200 200 image width
500 500 nbx,ny
1.5 1.5 hx,hy smoothing (pixel units)
```

Again, not all the parameters are detailed here, the file itself being very well commented. Only the parameters that might be important for a beginner are shown.

1. The path should only specify where the output folders are located, not the output folders themselves. Thus, \( \text{./output}_0001 \) will not be recognised.

2. COM reset subtracts the center of mass position and velocity. It could be used if the object of interest lies outside the field of view.

To just extract the particle positions and velocities, only parameters until the Partial COM section are important. After setting the parameters, execute:

\[
\text{$ ./xpor\ data $}
\]

Based on the number of output files selected, the corresponding number of part.asc and sfr.dat files will be created. The part.asc files contain data in ascii format with the following column meanings:

1–3: position, 4–6: velocity, 7: mass, 8: particle ID

The sfr.dat file contains:

1: time interval in Myr, 2: SFR in M\(_{\odot}\)/Myr

The extraction algorithm calculates the total stellar mass in a given snapshot, and evaluates the difference in stellar mass between two snapshots. One can resolve the SFR better by changing \( \delta\text{tout} \) in the namelist file, or by extracting particle birth times.

Any tool can be used to extract and plot the results from the part.asc files. Even extract\_por can be used for plotting, in which case all the sections below Image Params can be helpful. These sections can be used to set the projected density, resolution etc. To use extract\_por for plotting, the following suggestions might be helpful:

1. In Image_params, unless one has a special case like [36], using 2:rgb or 3:rgbw is not helpful. Set it to 1:gray. This works and one can set the required projected density.

2. The use of binning radius might be critical for resolution. In case of poor resolution, increase the number of bins. To increase the pixel resolution/zoom in, reduce the image field of view in fmtRAMSES.par, i.e. reduce the bin sizes.

3. Users could set the box width equal to the simulation box size and locate the galaxy manually.

4. \( \text{ hx and hy smoothing } \) smoothens the image. This can be changed based on needs.

5. All parameters below \( \text{ hx, hy smoothing } \) are not to be changed.

Run extract\_por and expect two output files to be produced:

1. part.asc

2. image.dat

The image.dat has the data required for plotting the image (particle positions). The simplest way is to use gnuplot:

\[
\text{$ gnuplot \rightarrow plot \text{‘image.dat’ with image } $}
\]
7. Tests and publications using POR

Since its development in 2015, POR has been applied to a variety of problems. A first implementation showed that the observed dynamics in polar ring galaxies is explained naturally in MOND [37]. [38] compared Antennae-like galaxy encounters in MOND and in dark matter models, studying the evolution towards merging and the triggering of star formation in both models. The Galactic tidal streams of Sagittarius [39] and Palomar 5 [40] were investigated as gravitational experiments, with the latter’s asymmetry interpreted as evidence for the EFE. [41] showed that the satellite galaxy planes of the MW and M31 might arise from a past encounter between them. [42] showed that exponential disc galaxies form naturally in MOND out of collapsing post-Big Bang gas clouds. [32] simulated M33, finding that its long-term evolution is well understood in MOND, especially its weak bar and lack of a bulge. Their work also details some of the numerical methods, especially in H-DICE and the extfield patch.

8. Conclusions

POR [11] is a general-purpose N-body and hydrodynamical solver for MOND. It is based on adapting RAMSES, whose modern version is not compatible with the POR patch. It is recommended to use POR from here in. This manual is a generic outline with which one can understand the basics required to set up, run, and analyse POR simulations. The above-mentioned files like the namelist and patches like staticpart and hydro are custom-made for a specific purpose, so care should be taken before using them for a different application. All the algorithms and tools mentioned in this guide are available here in, and are rated to work.

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