Using CMHOG with NEMO and MIRIAD

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Abstract

An overview is given how to use and extend the Piner, Stone & Teuben (1995, ApJ 449, 508) hydro code `cmhog`, and in particular how HDF[1] output data can be used with NEMO and MIRIAD for some basic visualization and data analysis. Only single runs are covered, restart runs are not discussed here. An unfortuitous bug that combined a wrong bar position angle and reversed the azimuthal forces from the bar was fixed in 2011, and updated results are further discussed in Kim, Seo, Stone, Yoon & Teuben (2011)

1 Introduction

The "`cmhog`" code is an isothermal PPM code, that was adopted to run a 2-dimensional polar-grid gas flow in a barred galaxy (Piner, Stone & Teuben, 1995 ApJ 449, 508). Because of symmetry, only half of the plane is normally simulated, with the appropriate boundary condition. The bar is elongated along the Y-axis, with counter clockwise gas flow. Initially the bar is absent, but slowly (usually 0.1Gyr) turned on while keeping the total mass constant. The simulation is usually followed for 1-2 Gyr, to settle into a quasi-stationary state, at which time the gas properties (density, flow velocities) can be studied and compared to observations.

2 The "cmhogin" input file

The `cmhog` program uses a classic, but not often used, method of parameter input that is a little more rubust to errors than the more often (ab)used method of reading information from standard input or some user defined file. It's called `namelist`, a specially formatted textfile, and works roughly like magically reading a FORTRAN named common block. in one read, with a convenient way to set defaults for all values in the program.

[1] `cmhog` only writes the HDF4/SDS data format, no HDF5!

2.1 For the programmer

For the programmer it is very convenient to pass parameters via a namelist. After opening the unit somewhere at the beginning of the program (cmhog does this in `mstart.src`) various subroutines can simply read the namelist that they need with a simple read statement.

```
open(unit=1,file='cmhogin' ,status='old')                    ::mstart.src

real*8 amp,amode,n,aob,qm,rhoc                               ::galaxy.src
real   bartime
namelist /pgen/ amp,npar,amode,n,aob,rl,qm,rhoc,bartime
read (1,pgen)

logical lgrid
namelist /ggen2/ nbl,ymin,ymax,igrid,yrat,dymin,vgy,lgrid    ::ggen.src
namelist /ggen3/ nbl,zmin,zmax,igrid,zrat,dzmin,vgz,lgrid
read (1,ggen2)
```

2.2 For the user

For the user this means all parameters are set in a simple ascii file named "`cmhogin`" that can be edited. This file must be in the current directory when `cmhog` starts to run (see also `runcmhog` below for an alternative approach). Here is a sample `cmhogin` file:[2]

```
$rescon  $end
$hycon idiff=1,ifltn=1,tlim=2.0 $end
$ggen2 nbl=132,ymin=0.1,ymax=16.0,yrat=1.03926991,igrid=1,lgrid=.true. $end
$ggen3 nbl=80,zmin=-1.5708,zmax=1.5708,igrid=1,lgrid=.true. $end
$ijb $end
$ojb $end
$ikb $end
$okb $end
$eos ciso=5.0 $end
$pgen amp=10.0,amode=1.0,n=1.0,aob=2.5,rl=6.0,qm=4.5e4,rhoc=2.4e4,bartime=0.1 $end
$spiral spamp=0.0,spang=-0.5236,spsc=1.0,sppat=32.74,sr=4.0,pc=2.328 $end
$pgrid $end
$iocon dthdf=0.1,dtmovie=5.0,dthist=0.01 $end
$mlims cma1=3.0,cmi1=-2.0,cma2=200.0,cmi2=-200.0,cma3=200.0,cmi3=-200.0 $end
```

[2] g77 would allow namelist lines to end in `$`, in gfortran `$end` is needed

When `cmhog` finishes, the file `cmhogout` will reflect the full status of the namelist, not just the variables entered via the `cmhogin` file.

The most common ones to modify are (geometry in `ggen2` and `ggen3` will be dicussed later)

- `pgen/aob` Axis ratio a/b of the bar, note it will be > 1.
- `pgen/rl` Lagrangian radius, in kpc, along bar axis. This then sets the pattern speed.
- `pgen/qm` Quadropole moment, this sets the mass fraction of the bar.
- `pgen/rhoc` Central density, this sets
- `pgen/bartime` Time for the bar to (linearly) grow to full strength (in Gyr)
- `iocon/dthdf` Timestep for HDF (HDF4/SDS) data dumps (in Gyr)
- `icon/dtmovie` Timestep for `mde/mvt/mvr` data dumps (in Gyr). These are not very useful actually, they are 8 bit deep. If set to 0 (the default) none will be produced.
- `icon/dthist` Timestep in `history` file (in Gyr)
- `hycon/tlim` Stop time of the integration (in Gyr)
- `pgrid/pot0` A fits file that contains the axisymmetric part of the potential on a grid. Length units must be kpc, and the potential must be defined on the whole grid, in particular out to a radius of `ggen2/ymax` kpc.
- `pgrid/pot1` A fits file that contains the non-axisymmetric part of the potential on a grid. Length units must be kpc.
- `pgrid/omega` Pattern speed if you want to override the value derived from `pgen/rl`
- `pgrid/vhalo` Background (softened isothermal) halo potential asymptotic velocity.
- `pgrid/rhalo` Background (softened isothermal) halo potential core radius.
- `pgrid/gamma` Scaling factor for the grid potential. This acts like an M/L factor, but is only used when a halo (vhalo>0) is used. Once the halo is added this gamma factor can be used to determine the amount of the disk contribution w.r.t. maximum disk.
- `pgrid/naxis1 ,pgrid/naxis2, pgrid/rmax` Setting only these will generate an internal grid, instead of the external grid on pot0/pot1. It's really a cheat and meant for debugging potentials. `rmax` is also needed, and defines the maximum extent of the grid in X and Y.

- `pgrid/rtstart,pgrid/rtscale` The starting radius, and scale-length (in kpc) where an exponential taper is applied to the non-axysymmetric part of the potential. Normally the defaults are such (1000,1000) that a taper is not applied.
- `pgrid/rnstart,pgrid/rnscale` The starting radius, and scale-length (in kpc) within which a nuclear tapering is applied. This is needed to ensure that near the center the potential is sufficiently axisymmetric to prevent gas flow to concentrate on the center, and not some point slightly off-centered. This can often occur for grid potentials derived from observations. Normally the defaults are such (-1000,1000) that a taper is not applied.

2.3 Choice of the grid

The grid is a polar grid, and set by the `ggen2` (radial, the Y variable) and `ggen3` (angular, the Z variable) namelist entries, of which the `min` and `max` variables control the inner and outer edges of the grid in that dimension resp. The code in `ggen.src` will read the namelists and generate a grid.

```
$ggen2 nbl=132,ymin=0.1,ymax=16.0,yrat=1.03926991,igrid=1,lgrid=.true. $
$ggen3 nbl=80,zmin=-1.5708,zmax=1.5708,igrid=1,lgrid=.true. $
```

We suggest the following procedures, mirroring the `igrid=1` and `igrid=2` cases in the `ggen3` namelist:

1. choose `ggen2/ymin` $= y_{min}$, the inner radial boundary of the grid (in kpc). We normally choose 0.1
2. choose `ggen2/ymax` $= y_{max}$, the outer radial boundary of the grid (in kpc). We normally choose 16.
3. choose `ggen2/nbl` $= N_y$, the number of radial zones.
4. choose `ggen2/yrat` $= f$, it should be a little over 1, probably around

$$f \approx \frac{y_{max}}{y_{min}}^{1/N_y}$$

   this formulae is based on a simple geometric growth of the cell edges, in reality it are the cell sizes that grow geometrically with f.

5. Compute `ggen3/nbl` $= N_z$, the number of angular zones, such that cells are close to being square from the following relationship that equates the angular and radial zone size near at inner boundary:

$$\frac{\pi y_{min}}{N_z} = dy_{min} = (y_{max} - y_{min})\frac{f-1}{f^{N_y}-1}$$

or

$$N_z = \frac{\pi}{\frac{y_{max}}{y_{min}} - 1} \frac{f^{N_y} - 1}{f - 1}$$

The N_z computed this way is not an integer, but if rounded to the nearest, the zones will be square enough for large enough N. An alternative is to find the value of f that results in an exact integer value. For this a Newton-Raphson search is needed (see below).

6. Set `ggen3/zmax` $= z_{max}$ to $\pi/2$ for a half-symmetric plane.
7. Set `ggen3/zmin` $= z_{min}$ to $-\pi/2$ for a half-symmetric plane.

A NEMO program `grid` is distributed with `cmhog2` to aid in choosing a grid with decent properties. In default mode it will follow the above procedure, e.g.

```
 % grid ny=251 ymin=0.1 ymax=16 yrat=1.02043
ny=251 ymin=0.1 ymax=16 yrat=1.02043 dymin=0.00204079 dz=0.00204
       nzy=153.94 est_yrat=1.02043 igrid=1
```

suggests that for this choice of `yrat` the number of angular zones should be $N_z = 154$.

An alternative approach is to first fix the number of angular zones, which through the desired square grid determines `dymin`, from which then `yrat` can be computed:

1. choose `ggen2/ymin` $= y_{min}$, the inner boundary of the grid (in kpc). We normally choose 0.1
2. choose `ggen2/ymax` $= y_{max}$, the outer boundary of the grid (in kpc). We normally choose 16.
3. choose `ggen3/nbl` $= N_z$, the number of angular zones
4. choose `ggen2/nbl` $= N_y$, the number of radial zones.
5. set `ggen2/dymin` from the requirement that the grid should be close to square, i.e.

   $$dy_{min} = \frac{\pi y_{min}}{N_z}.$$

   Compute `ggen2/yrat` $= f$, by solving for

   $$\frac{\pi y_{min}}{N_z} = (y_{max} - y_{min}) \frac{f - 1}{f^{N_y} - 1}$$

   For this a Newton-Raphson search is needed. It should be noted here that f should not be too different from 1, e.g. 1.05 is ok, but not much larger. This is because higher-order schemes like PPM rely on a fortuitious cancellation of truncation error which only occurs if the grid size is uniform. As you make f much different than one, this uncancelled error can become significant.

6. Set `ggen3/zmax` = z_{max} to $\pi/2$ for a half-symmetric plane.

7. Set `ggen3/zmin` = z_{min} to $-\pi/2$ for a half-symmetric plane.

```
 % grid ny=251 ymin=0.1 ymax=16 nz=154 dymin="pi*0.1/154"
ny=251 ymin=0.1 ymax=16 yrat=1.02043 dymin=0.00204 dz=0.00204
       nzy=154 est_yrat=1.02043 igrid=2
```

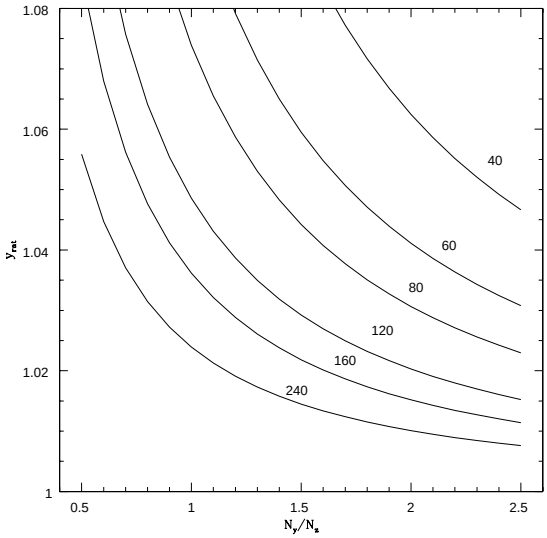


Figure 1: The zone expansion factor, `yrat`, as a function of the ratio of radial to angular zones, for a few selected values of the number of angular zones.

3 Output Files

For the remainder of the discussion, we will assume all data produced by `cmhog` is dumped in a run-directory. In general, it is a good idea to remove any potential files `cmhog` may create, though in practice only the `hdfXXXbg` files are the problem makers (by default data would be appended to any existing HDF files).

Depending on options given to the program, you may find the following files in your run directory:

- `cmhogin` Input namelist, that controls the program. This is generally the only input file (except if pgrid is used, two fits files will be input files).
- `cmhogout` Output namelist, reflects current state of all variables.

- `history` Ascii table with time in the first column, other columns are used for things such as mass loss across the inner and outer boundaries etc.etc.
- `hdfXXXbg` Full HDF dataset, in HDF4/SDS format (Scientific Data Set), typically with three named "fields": the `R-VELOCITY`, `PHI-VELOCITY`, and `DENSITY`. The NEMO program `tsd` will display the contents of such SDS files. Each file contains information for one timestep. `hdf0000bf` is normally the first one, for $t = 0$ at the beginning of the simulation.
  NOTE: Existing dataset will get their new SDS's appended to the previous ones. Most scripts that will be discussed in this paper, will then break.
- `mdeXXXbg` Sample X-Y gridded density in a 8bit deep image (if `dtmovie` > 0)
- `mvrXXXbg` Sample X-Y gridded radial velocity in a 8bit deep image (if `dtmovie` > 0)
- `mvtXXXbg` Sample X-Y gridded tangential in a 8bit deep image (if `dtmovie` > 0)

Although the author has mostly used NEMO for analysis and visualization, there is a native NCSA program which can be used to quickly just look at the numbers.

```
% hdp dumpsds -i <index> -d <hdf_file>
```

which writes only the data of set with index `index`. Index 0 are the phi values, index 1 are the radial values, and those are repeated in 3,4 and 6,7. The v, w and d data is in sets 2, 5 and 8. To get the dimensions, use -h instead of -d on sets 0 and 1 to get the header (not the data) and grep for the 'Size =' line. Not all that pretty but it all works!

```
% hdp dumpsds -i 0 -d hdf0001bg                # PHI (vector)
% hdp dumpsds -i 1 -d hdf0001bg                # R (vector)
% hdp dumpsds -i 2 -d hdf0001bg                # R-velocity (matrix)
% hdp dumpsds -i 5 -d hdf0001bg                # PHI-velocity (matrix)
% hdp dumpsds -i 8 -d hdf0001bg                # DENSITY (matrix)
```

4 NEMO programs

Most, if not all, NEMO programs come with a manual page that should explain the command line parameters (keywords) in more detail.

4.1 runcmhog

`cmhog` is a program that needs to be run in a clean directory, and you cannot run another `cmhog` in that directory. That is because the names of files that `cmhog` produces are FIXED by the program, and cannot be changed even by the `cmhogin` file (it is also not practical to do that). To help running `cmhog`, a small pre-processor was written, called `runcmhog`. It is a little C program available in NEMO with which you can use a template `cmhogin` file and override parameters and set a run directory, e.g.

```
% runcmhog -n cmhogin.small run001  aob=2.0
% runcmhog -n cmhogin.small run002  aob=2.5
% runcmhog -n cmhogin.small run003  aob=3.0
% runcmhog -n cmhogin.small run004  aob=3.5
```

Jianjun Xu (a student of Jim Stone) once wrote a nice graphical frontend, based on Tcl/Tk, to parse and generate cmhogin files. The code still exists, but has not been excersized in a long time.

4.2 tsd

`tsd` scans an HDF SDS :

```
% tsd hdf0001bg
Found 3 scientific data sets in run001/hdf0001bg
1: R-VELOCITY AT TIME=1.00E-01(20,37) km/sec  -> [740 elements of type: 5 (FLOAT32)]
2: PHI-VELOCITY AT TIME=1.00E-01(20,37) km/sec  -> [740 elements of type: 5 (FLOAT32)]
3: DENSITY AT TIME=1.00E-01(20,37) Msolar/pc**2  -> [740 elements of type: 5 (FLOAT32)]
```

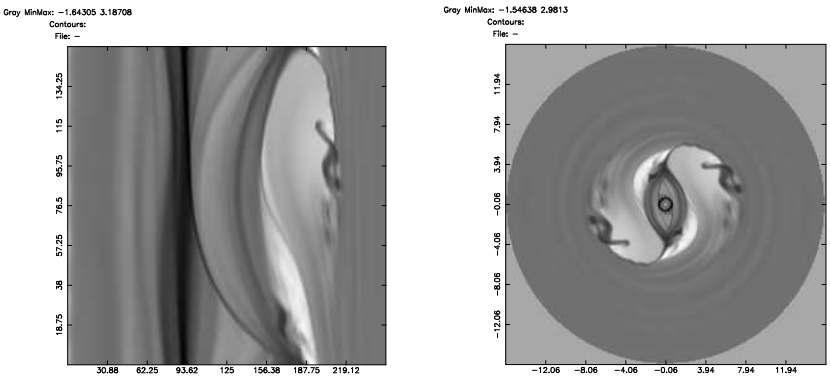
but can also print out data values and the coordinate system. In our case, the first axis is the radial coordinate, and will not be a regularly sampled axis. The second axis is the angular coordinate, and will be regularly sampled (normally between $-\pi/2$ and $\pi/2$).

Here is an example of getting the "rotation curve" from T=0. First we need to run `tsd` again, just to confirm how many radii we have, in this case the 2nd dimension listed in the output of the arrays.

```
% tsd hdf0000bg
Found 3 scientific data sets in hdf0000bg
1: R-VELOCITY AT TIME=0.00E+00(40,67) km/sec  -> [2680 elements of type: 5 (FLOAT32)]
2: PHI-VELOCITY AT TIME=0.00E+00(40,67) km/sec  -> [2680 elements of type: 5 (FLOAT32)]
3: DENSITY AT TIME=0.00E+00(40,67) Msolar/pc**2  -> [2680 elements of type: 5 (FLOAT32)]
% tsd hdf0000bg - coord=t | head -67 | tabplot - 1 4
```

4.3 sdsfits

The individual "fields" from an `hdfXXXbg` files can be converted to FITS files, for visual inspection. Just remember that the first axis is the radial axis, the second one the angular. A ring will thus show up as a vertical structure.



(a) Polar coordinates (b) Cartesian coordinates

Figure 2: Logarithmic density in polar coordinates:

```
% sdsfits hdf200bg mapd.fits 3
% fitsccd mapd.fits - | ccdmath - - 'log(%1)' | ccdplot -
yapp=denrt.ps/vps
Logarithmic density in cartesian coordinates:
% hdfgrid hdf200bg - 3 | ccdmath - - 'log(%1)' | ccdplot -
yapp=den.ps/vps
```

```
% sdsfits hdf0001bg map001vr.fits 1
% sdsfits hdf0001bg map001vt.fits 2
% sdsfits hdf0001bg map001de.fits 3
```

Here is another plot:

```
% fitsccd mapd.fits - | ccdmom - - axis=2 mom=0 | ccdprint - x= newline=t | tabplot - 0 1 line=1,1
```

it plots total density averaged in rings, as function of cell.

4.4 hdfgrid

`hdfgrid` regrids selected gas properties from our HDF files into a cartesian coordinate system. It is specific to this polar-coordinate problem.

```
% hdfgrid hdf0001bg map000de.ccd zvar=den
% hdfgrid hdf0001bg map000vr.ccd zvar=vr
% hdfgrid hdf0001bg map000vt.ccd zvar=vt
% hdfgrid hdf0001bg map000vx.ccd zvar=vx
% hdfgrid hdf0001bg map000vy.ccd zvar=vy
```

Note that the `vx` and `vy` velocity fields are computed on the fly. Nearest neighbor cells are used for bi-linear interpolation. Some assumptions about the symmetry properties of the variables have been made, in case only a half-plane was computed.

5 flowcode

Although gas flow in a barred galaxy never reaches an exact steady state, it does approach something that can perhaps be called a QSSS. However, another approach to understand the gas flow is take a particular snapshot, and integrate test particles in the velocity field, i.e. solve the equations

$$\frac{dx}{dt} = V_x(x, y)$$

and

$$\frac{dy}{dt} = V_y(x, y)$$

NEMO's `flowcode` program does that. For this a special "vrt" file (NEMO image format) is needed as input for the integrator, consisting of two 2D images with VR and VT, followed by two 1D images with the coordinates in Radius and Polar Angle (called PHI) A "vrt" map is created with a script `mkvrt`.

```
In NEMO you will have to compile flowcode, e.g.

mknemo flowcode

but also the .so files:

cd $NEMO/src/nbody/evolve/flowcode
make vrt.so vrtd.so
cp *.so $NEMOOBJ/potential
(sorry, no make target yet....)


The so-called ‘‘vrt’’ and ‘‘vrtd’’ files are to be made from HDF files,
with the script mkvrt and mkvrtd that didn’t come with flowcode yet
...(catch-22)..

Here is an example of use: the initial conditions is gas flow on
circular orbits, so we’ll integrate the flow and see if they remain
on circular orbits:

mkvrt hdf0000bg test0000.vrt
```

5.1 NEMO scripts: mkbar

Shell scripts are probably currently the easiest way to setup problems. In order to make them reusable, much like NEMO programs, they should take a series of *"keyword=value"* command line arguments.

```
#! /bin/csh -f
#
#
#> nemo.need mkconfig snapadd snapscale snaprotate snapspin

# bar length and axis ratio of bar
set b=1.4
set q=0.2

#
set n=100

# derived quantities
set phi=‘nemoinp "atand($q)"‘

rm bulge line1 line2 bar disk model.dat

mkconfig - $n shell "$q*$b" | snapscale - bulge 1 1,1,0.4
mkconfig - $n line $b | snaprotate - -  90-$phi z | snapshift - line1 "-$q*$b,0,0"
mkconfig - $n line $b | snaprotate - - -90-$phi z | snapshift - line2 "$q*$b,0,0"
mkconfig - $n ring $b | snapscale - bar 1 $q,1,1
mkconfig - $n ring 2  | snapspin - disk 1
snapadd disk,bulge,line1,line2,bar model.dat
```

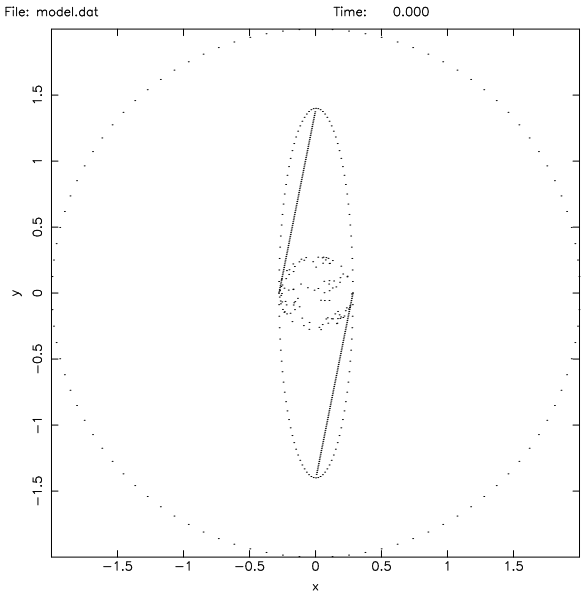


Figure 3: Face on view of a simple schematic for a counter-clockwise rotating bar, as is used in the hydro models:
`% snapplot model.dat yapp=model1.ps/vps`

5.2 NEMO scripts: project

Projecting a bar to match observations takes 3 geometric parameters: position angle and inclination of the galactic disk, and position angle of the bar, all measured from the sky. In addition there will be centering (xpos,ypos,vsys) and scaling (pscale, vscale) parameters, that will come later. To aid in figuring out the geometric projection, a script `project` was written, that projects the model from the previous section. It is somewhat taylored for the way we measure angles in astronomy. In here `phi` is defined as the angle between bar and disk, as measured in the plane of the sky.

```
#! /bin/csh -f
#
#> SCALE inc=0 0:90:1
#> RADIO rotation=ccw   ccw,cw
#> SCALE pa=0 -180:180:1
#> SCALE phi=0 -90:90:1
#> RADIO yapp=/xs       /xs,/vps,/ps,/gif
#> ENTRY text=


foreach a ($*)
  set $a
end

if ($rotation == "cw") then
  snaprotate model.dat - "atand(tand($phi)/cosd($inc+180)),$inc+180,$pa" zyz |\
    snapplot - psize=vz/4 yapp=$yapp xlabel="inc=$inc ($rotation) pa=$pa phi=$phi" "ylabel=$text"
else
  snaprotate model.dat - "atand(tand($phi)/cosd($inc)),$inc,$pa+180" zyz |\
    snapplot - psize=vz/4 yapp=$yapp xlabel="inc=$inc ($rotation) pa=$pa phi=$phi" "ylabel=$text"
endif
```

This script uses NEMO's `tkrun` interface, so you need to run it as follows:

```
% tkrun project
```

5.3 NEMO scripts: mkbar_cube_ref.csh

The script listed below is an older one where the geometry (cw/ccw) was not properly programmed, but included for completeness. It will use a reference cube (`n4303cube.fits`) to aid in matching up the theoretical data with an observation.

```
#! /bin/csh -f
#
#  This scripts takes an HDF output snapshot file from cmhog
#  (bar hydro, polar coordinates), projects it to a requested
#  sky view, and using WIP summarizes the results
#  Bar is conveniently oriented along Y axis (PA=0), and flows CCW.
#  For CW rotating galaxies you may have to add 180 to 'inc' and/or 'pa'
#
#
```

```
#  23-sep-95 Created Peter Teuben
#  15-nov-95    beam=0.2 frang=45
#  24-nov-95    defaults for more central region, fixed dependancies
#   9-jul-96    hacking for N5383
#  24-jul-00    BIMA proposal N4303 et al.
#   5-sep-00    modified to write cubes instead of moment maps
#  12-mar-01    radecvel=t to make karma swallow these fits files
#  13-mar-01    use phi,inc,pa (no more +/- 180) and documented geometry
#               (notice that earlier versions had sign of radial vel wrong)
#  23-mar-01    added a refmap and fixed refscale; this assumes that the refmap
# (often a cube) has the reference pixel defined to the be
# center of the galaxy (bimasong data often don't do the VELO axis correct)
#  17-apr-01    added velocity referencing using 'vsys' to be at v=0 in the model cube
#               (bugs when model and data have different delta-V)
#  11-apr-02    generic version with new geometry definitions

if ($#argv == 0) then
  echo Usage: $0 in=HDF_DATASET out=BASENAME ...
  echo Gridding and projecting 2D CMHOG hydro models to given bar viewing angles
  exit 0
endif

#  Required Keywords
unset in
unset out
#  Defaulted Keywords
set pa=-42
set inc=27
set phi=44
set rot=1
#
set rmax=6
set n=200
set beam=0.05
set color=1
set clean=1
#
set refmap=""
set pscale=0.5
set vscale=1
set vsys=0
# Velocity gridding for cube  (dv=2*vmax/nvel)
set nvel=50
set vmax=250

set par=""

# Parse commandline to (re)set keywords, special case for par=
foreach a ($*)
  set $a
  if (-e "$par") then
    source $par
    set par=""
  else
    echo Warning, par=$par does not exist
    set par=""
  endif
```

```
end

#
#  fix inc/pa for ccw(rot=1) or cw(rot=-1) cases for NEMO's euler angles
#
if ($rot == -1) then
   set inc=$inc+180
else if ($rot == 1) then
   set pa=$pa+180
else
   echo "Bad rotation, must be 1 (ccw) or -1 (cw)"
   exit 1
endif

# Show i'm happy
echo Files: in=$in out=$out
echo Grid: rmax=$rmax n=$n beam=$beam
echo Projection: phi=$phi inc=$inc pa=$pa
#                       Derived quantities
set cell=`nemoinp "2*$rmax/$n"`
set range="-${rmax}:${rmax}"
echo "      Derived: cell=$cell"

if (-e "$refmap") then
    #   referencing
    set nz=(`fitshead $refmap | grep ^NAXIS3 | awk '{print $3}'`)
    set pz=(`fitshead $refmap | grep ^CRPIX3 | awk '{print $3}'`)
    set vz=(`fitshead $refmap | grep ^CRVAL3 | awk '{print $3}'`)
    set dz=(`fitshead $refmap | grep ^CDELT3 | awk '{print $3}'`)

    set dz1=`nemoinp "2000*$vmax/$nz"`
    set vref=`nemoinp "($vz-1000*$vsys)/($dz1)+$nvel/2+0.5"`
    #set vscale=`nemoinp "$vscale*(2*$vmax/$nvel)/($dz/1000)"`
    set refscale=$pscale,$pscale,$vscale
    #                                   CHECK : is this -0.5 or +0.5   ?????
    set refcen=`nemoinp $n/2-0.5`
    #set refpix=$refcen,$refcen,$vref


    #   now assuming model is centered, as well as data cube
    set vref=`nemoinp $nvel/2+0.5`
    ###set vref=`nemoinp $nvel/2-0.5`
    set refpix=$refcen,$refcen,$vref


    echo $nz $pz $vz $dz
    echo Vsys at OBS pixel: `nemoinp "(1000*$vsys-$vz)/$dz+$pz"`
    echo REFPIX:   $refpix
    echo REFSCALE: $refscale
else
    echo BUG: need to rewrite this section for when no refmap given..... since you did not
    exit 1
endif

#> nemo.need tabtos snaptrans snaprotate snapadd snapgrid ccdsmooth ccdmath ccdfits fitshead

set tmp=tmp$$
```

```
if (! -e $out.den.fits) then

    # convert the half-plane HDF file to a full plane snapshot file

    tsd in=$in out=$tmp.tab coord=t
    if ($status) goto cleanup
    tabtos in=$tmp.tab out=$tmp.s0 block1=x,y,vx,vy,mass
    snaptrans in=$tmp.s0 out=$tmp.s1 ctypei=cyl ctypeo=cart
    snaprotate in=$tmp.s1 out=$tmp.s2 theta=180 order=z
    snapadd $tmp.s1,$tmp.s2 $tmp.s3

    # project for skyview, and create a intensity and velocity field

    snaprotate $tmp.s3 $tmp.snap \
        "atand(tand($phi)/cosd($inc)),$inc,$pa" zyz

    foreach mom (0 1 2)
         snapgrid in=$tmp.snap out=$tmp.$mom \
                xrange=$range yrange=$range nx=$n ny=$n moment=$mom mean=t
         ccdsmooth in=$tmp.$mom out=$tmp.$mom.s gauss=$beam
    end
    ccdmath $tmp.1.s,$tmp.0.s $tmp.vel %1/%2
## BUG: ifgt() doesn't work
##    ccdmath $tmp.0.s - "ifgt(%1,0,log(%1),-10)" | ccdfits - $out.den.fits
    ccdmath $tmp.0.s - "log(%1)" | ccdmath - - "ifeq(%1,0,-10,%1)" | ccdfits - $out.den.fits  \
        object=$in comment="$0 $in $out $pa,$inc,$phi,$range,$n,$beam"  \
refmap=$refmap scale=$refscale refpix=$refpix
    ccdmath $tmp.2.s,$tmp.0.s,$tmp.vel - "sqrt(%1/%2-%3*%3)" | ccdfits - $out.sig.fits \
        object=$in comment="$0 $in $out $pa,$inc,$phi,$range,$n,$beam"  \
refmap=$refmap scale=$refscale refpix=$refpix
    ccdfits $tmp.vel $out.vel.fits \
        object=$in comment="$0 $in $out $pa,$inc,$phi,$range,$n,$beam"  \
refmap=$refmap scale=$refscale refpix=$refpix


### BUG:      ccdmath - - "ifgt(%1,0,log(%1),-10)" |\


    # now also create the (smoothed) cube
    snapgrid in=$tmp.snap out=- \
          xrange=$range yrange=$range zrange=-${vmax}:${vmax} \
  xvar=x yvar=y zvar=-vz \
  nx=$n ny=$n nz=$nvel moment=0 mean=t |\
      ccdsmooth - - gauss=$beam |\
      ccdmath - - "log(%1)" |\
      ccdmath - - "ifeq(%1,0,-10,%1)" |\
      ccdfits - $out.cube.fits \
        object=$in comment="$0 $in $out $pa,$inc,$phi,$range,$n,$beam" \
refmap=$refmap scale=$refscale refpix=$refpix

    rm -fr $tmp.*
else
    echo Warning: skipping gridding and projecting
endif

exit 0
```

```
cleanup:
    if ($clean) rm $tmp.*
```

6 Stellar Orbits

7 cmhog: the Program

Files are .src (fortran source to be pre-processed by cpp) and .inc (for the pre-processor) and .h (standard fortran includes). On some operating systems (e.g. GNU/linux) the use of `cpp` as a pre-processor meant that single quotes could not be used in fortran comments.

```
    main
        mstart
    setup
    grid_generator    (ggen)
    problem_generator (galaxy)
    nudt
        dataio

solver
intchk
dataio
special
nudt

dataio
```

7.1 Potential

The potential and forcefield are defined through two subroutines named `inipotential` and `potential`. They follow the standard way how potentials are coded in the NEMO environment, with the advantage that a variety of NEMO programs are now acccessible to investigate such potentials. Within NEMO potentials can be written in either Fortran or C, although in order for `cmhog` to make use of them, any C version would need the usual interface layer between Fortran and C. The standard distribution of the bar hydro project of `cmhog` implements the potential in `piner94.src`, which is (or should be) identical to the one in `$NEMO/src/orbit/potential/data/piner94.f`.

The standard "piner94" potential is fixed in size by setting the bar length to 5kpc and the velocity amplitude at 20 kpc to 164.204 km/s (see discussion in Athanassoula 1992)

The following are the standard "potpars" parameters to this potential.

```
omega           normally set to 0, since it is derived from ‘‘lagrad’’, and returned in th
amode           not used [0]
index           power of bar density law, not used ? [1]
axirat          Axis ratio a/b of the bar (a number > 1) [2.5]
radlag          Lagrangian radius along the bar axis, defined where the forces balance [6.
quad            Quadrupole moment, measures the bar strength [45,000]
cenden          Central Density, sets the slope of the central velocity field [24,000]
                (or equivalently, the core radius)
```

7.2 Potentials on a grid

In the fall of 2002 the `cmhog` code was modified to handle potentials on a grid. Two additive potentials, as FITS files, can be given in the (new) **pgrid** directive in the `cmhogin` file. The coordinate system in the FITS file, as defined by the usual CRVAL/CRPIX/CDELT keywords in the FITS header, must be linear and in KPC (typically covering -16 to 16 kpc or so, but perhaps a little more to handle the edges).

The following shell snippet shows how to create a potential:

```
% potccd grid0 athan92 0,1,1,2.5,6.5,0,24000 x=-17.5:17.5:0.07 y=-17.5:17.5:0.07 omega=0
% ccdfits grid0 grid0.fits
% fitshead grid0.fits

SIMPLE  =                    T /
BITPIX  =                  -32 /
NAXIS   =                    3 /
NAXIS1  =                  501 /
NAXIS2  =                  501 /
NAXIS3  =                    1 /
COMMENT  FITS (Flexible Image Transport System) format is defined in 'Astronomy
COMMENT  and Astrophysics', volume 376, page 359; bibcode: 2001A&A...376..359H
CRPIX1  =      1.000000000E+00 /
CRPIX2  =      1.000000000E+00 /
CRPIX3  =      1.000000000E+00 /
CRVAL1  =     -1.750000000E+01 /
CRVAL2  =     -1.750000000E+01 /
CRVAL3  =      0.000000000E+00 /
CDELT1  =      7.000000030E-02 /
CDELT2  =      7.000000030E-02 /
CDELT3  =      0.000000000E+00 /
CTYPE1  = 'X       '           /
CTYPE2  = 'Y       '           /
```

```
CTYPE3  = 'Z       '           /
DATAMIN =     -2.563205781E+05 /
DATAMAX =     -4.864591797E+04 /
ORIGIN  = 'NEMO    '           /
AUTHOR  = 'teuben  '           /
OBJECT  = '        '           /
COMMENT
HISTORY  NEMO: History in reversed order
HISTORY  ccdfits grid0 grid0.fits VERSION=5.0
HISTORY  potccd grid0 athan92 0,1,1,2.5,6.5,0,24000 x=-17.5:17.5:0.07 y=-17.5:1
         7.5:0.07 omega=0 VERSION=1.4
END
```

8 Installation

The best way to obtain cmhog is via git:

```
        git clone https://github.com/teuben/cmhog2
cd cmhog2
configure --help              (study the options you may which to use, see below)
configure
make cmhog
make bench


% configure --help
...
Optional Features:
  --disable-FEATURE       do not include FEATURE (same as --enable-FEATURE=no)
  --enable-FEATURE[=ARG]  include FEATURE [ARG=yes]
  --enable-cfitsio        enable it, the default is that it won't use CFITSIO

Optional Packages:
  --with-PACKAGE[=ARG]       use PACKAGE [ARG=yes]
  --without-PACKAGE          do not use PACKAGE (same as --with-PACKAGE=no)
  --with-pgmax=SIZE          Maxim size grid that can be read with cfitsio
  --with-cfitsio-prefix=PFX  prefix where cfitsio lives (lib,include or sourse)
```

8.1 Ubuntu

Here's an example of packages needed for Ubuntu22.04

```
    sudo apt install hdf4 hdf4-tools cfitsio gfortran make
```

8.2 CFITSIO

If compilation still fails, e.g. due to the CFITSIO interface, you may also manually need to edit the Makefile to the correct path of where CFITSIO (normally libcfitsio.a) is located. Also look at the cmhog.def file. Both files will be overwritten if you run `configure` though, so use the manual solution with care.

8.3 HDF4

It is also possible that your install fails due to an HDF4 problem (note that CMHOG2 uses the older version 4 of HDF, not HDF5). Recently the binaries that NCSA provides (e.g. for version 4.2.8) were compiled with `SZIP` compression enabled, although the default in the source code install is that it is disabled. If you see an undefined reference to `SZ_encoder_enabled`, you will either have to install the SZIP library, or re-install HDF4 with `configure --without-szlib`. If you have NEMO installed, look at `$NEMO/src/scripts/hdf.install`. As an example, for Ubuntu 12.04LTS, the system provided HDF4 libraries in /usr/lib work. On a bind, you can use a version of HDF4 we keep in our CVS repository. See the Makefile for details, but essentially the command would be to `make hdf4` from the `cmhog2` directory.

Note (2023) - compilation using HDF version 4.2.15-4 on Ubuntu22.04 worked.

8.4 autoconf

`cmhog` uses a file `configure.ac`[3]. The program `autoconf` produces a new version of `configure` from this file, might you need an updated version. The `configure` script will then transform the `Makefile.in` and `cmhog.def.in` into their working counterpart. You can see, by editing files such a `Makefile` and `cmhog.in` you run the risk of loosing your work on a subsequent installation.

[3]older versions of autoconf used `configure.in`

8.5 Benchmark

The `cmhog` benchmark is defined as running the standard PST95 model just through the bar growth time, 0.1Gyr, on a small 67×40 grid (see `cmhogin.bench`). This benchmark uses about $4.41665e6$ zone cycles The results for a few popular machines are summarized in Table 1.

- An Ultra-SPARC is about twice as efficient as an Intel chip.
- The Pentium-iii is about 10-15% more efficient per clock cycle than the Pentium-iv.
- The Intel compiler is about 30-40% more efficient compared to the GNU compiler (and it doesn't matter if this is on an intel or AMD chip)
- There is no benefit from using a 512kB cache size
- The Alpha is the most efficient processor per clock cycle (native compiler)
- Piv code running on a Piii chip will slow down the code considerably
- Compiler version can make a big difference

```
ratio of gnu to intel compiler on a Piv/2.2

 nphi    gnu    intel
  20    4.10     3.31
  40   26.43    21.08
  80  201.9    161.32
 154
```

Table 1: `cmhog` code benchmarks

Machine	MHz	cpu(sec)	cpu/GHz	K-zcs[4]	compiler/options
i7-1185G7	4800	1.50	7.2	2944	gfortran -g -O2
i7-3820	3600	3.39	12.2	1303	gfortran -g -O2
i7-3630QM	2400	3.58	8.6	1235	gfortran -g -O2
Intel i7 870	2930	5.22		846	g77 -g -O2
		4.76		928	
Core2Duo/T7300	2000	16.5	33.0	267.7	gfortran -O2
P-IV/512	3000	13.4	40.2		ifc -O2
		10.4	31.2	423.5	ifc -O2 -xW -tpp7 -ipo -i_dynamic
P-IV/512	2800	21.5			g77 -g -O2
		52.6			-g
		14.3			ifc -O2
P-IV/512	2200	26.3	57.8	76.4	g77 -g -O2
		20.6	45.3	97.5	ifc -O
		33.5			ifc -O2 -mp
P-IV	2000	29.4	58.8	75.1	
P-IV	1800	32.4	58.3	75.8	
P-IV	1600	42.2		104.6	g77 -g -O2
AMD	1600	23.1	37.0	119.4	
		17.6	28.2	156.6	ifc -O
P-III Coppermine	933	56.6	52.8	83.6	
		40.8	38.1	115.9	ifc -O
P-III	700	75.2	52.6	84.0	
P-III/512 Katmai	600	88.7	53.2	83.0	
P-III	600	91.1	54.7	80.7	(laptop)
		65.0	39.0	113.2	ifc -O
		70.8			pgf77 -O (version 3.2)
		93.6	56.2	78.6	ifc -O compiled on Piv
P-III/512 Katmai	500	106.5	53.3	82.9	
		89.5	44.3		gcc 3.2.2 @ mdk91
P-II/MMX	233	321.0	74.8	13.7	g77 -g -O2
		321.6	74.9	13.7	ifc -O
P-I	166	496.1	82.4	8.9	g77 -g -O2
G4	1400	29.7		148.8	g77 -g -O2
G4	800	60.5	-	79.9	g77 -g -O2
Alpha EV67	666	42.7	28.4	103.4	g77/gcc
		23.8	15.8	185.5	fort/ccc -fast
Ultra-SPARC-IIi	440	-	-		g77 -g -O2
		66.0	29.0	66.9	f77 -O
		55.0	24.2	80.3	f77 -fast ??
		44.0	19.4	100.4	f77 -fast
Ultra-SPARC	167	128.0	21.4	34.5	f77 -fast