Make Galaxy Guide

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1 INTRODUCTION

As discussed in the MCG guide, most spiral galaxies have reservoirs of rotating neutral HI gas. This gas is one of the best tracers of the galaxy's potential. Observations of the neutral HI emission of this gas using radio interferometers is in the form of spectral cubes.

MCGSuite is designed to be a standalone tool for generating realistic mock data cubes. This tool has three distinct components; the MockCubeGenerator program (hereafter MCG), and the pair of python wrapper programs make_galaxy_MCG.py and make_suite_MCG.py (hereafter make_galaxy and make_suite respectively). MCG is a tool for generating mock data cubes from tilted ring models, while the make_galaxy and make_suite programs are designed to generate realistic tilted ring models from scaling relations. make_galaxy makes a single mock data cube at a time, while make_suite generates a suite of data cubes with a variety of different parameters. It is important to note that the 'make_' programs are utilize scaling relations that only apply for a specific range of masses. In addition, the focus is on low to medium resolution observations, so the models are restricted to be axisymmetric.

The **MCG Guide** document focuses on tilted ring models and the MCG program. This document focuses on the usage of the make_galaxy and make_suite programs as well as how to use scaling relations to obtain tilted ring models. Sec. 2 describes the scaling relations used to generate rotation curve and surface density profile of the galaxy. Sec. 3 describes how those profiles are translated into tilted ring parameters. Secs. 4 and 5 describe the usage and outputs of the make_galaxy and make_suite programs respectively.

2 SCALING RELATIONS

The key goal of the 'make_' programs is to take a user specified HI mass and a set of observational parameters and generate realistic tilted ring model.

The first scaling relation is the correlation between the HI mass, $M_{\rm HI}$ and the HI radius, $R_{\rm HI}$ from Wang et al. (2016):

$$\log_{10}(D_{\rm HI}) = -3.293 + 0.506 \log_{10}(M_{\rm HI}) \ , \tag{1}$$

where $D_{\rm HI} = 2R_{\rm HI}$. By definition $R_{\rm HI}$ is the radius where the galaxy surface density is 1 $M_\odot$.

The second scaling relation is the correlation between the HI mass and the maximal velocity, $V_{\rm HI}$. This relationship is derived from the HI mass and HI velocity functions from the ALFALFA survey (Giovanelli et al. 2005, Haynes et al. 2018). A third order polynomial fit too the ALFALFA 40% catalogue (Haynes et al. 2011) gives

$$\log_{10}\left(v_{\rm HI}/{\rm km\ s^{-1}}\right) = 0.0345x_{\rm HI}^2 - 0.955x_{\rm HI}^2 + 9.134x_{\rm HI} - 27.99 \ , \tag{2}$$

where $x_{\rm HI} = \log_{10}(M_{\rm HI}/M_\odot)$.

These two scaling relations set the size of the galaxy and the rotational speed of the galaxy using only the HI mass. The next step is determining the actual rotation curve and the surface density profile. The surface density profile is set as the combination of a Gaussian and an exponential such that

$$\frac{\Sigma_{\rm HI}(R)}{\Sigma_{max}} = \exp\left(-\frac{(R-R_{\Sigma M})^2}{2\sigma_\Sigma^2}\right) + \left(1-\sqrt{\frac{V_{\rm HI}}{V_\Sigma}}\right)\exp\left(-R/R_{\Sigma S}\right) \ . \tag{3}$$

The exponential term adds mass to the center for low-mass system where the $V_{\rm HI}/V_\Sigma$ ratio is small. In higher mass systems the exponential term creates a central hole. Following (Dalcanton et al. 2004 and Kannappan et al. 2013), the exponential scaling terms are $R_{\Sigma S} = 0.2R_{\rm HI}$ and $V_\Sigma = 120{\rm km\ s^{-1}}$. For the Gaussian scaling factors we follow (Martinsson et al. 2016) and have $R_{\Sigma m} = 0.4R_{\rm HI}$. The maximum density, Σ_{max} is set such that $\Sigma(R_{\rm HI} = 1\ {\rm M_\odot\ pc^{-2}}$. Finally, we set $\sigma_\Sigma = 0.33R_{\rm HI}$ which then sets

$$M(R_{\rm HI}) = 0.85M_{\rm HI} \ , \tag{4}$$

which agrees with the measurements of (Wang et al. 2016).

Moving to the rotation curve, we use the Polyex function of (Giavanelli & Haynes 2002),

$$V_{rot}(R) = V_{PE}\left(1-e^{-R/R_{PE}}\right)\left(1+\frac{\alpha_{PE}R}{R_{PE}}\right) \ , \tag{5}$$

where V_{PE} is the scale velocity, R_{PE} is the turnover radius, and α_{PE} is the outer slope of the curve. These three parameters are determined using two sets of empirical relations; the inner rotation curve shapes of (Catinella et al. 2006) and the outer rotation curve trends of (Lelli et al. 2016). We fit the inner rotation curve data reported in Table 2 of Catinella et al. 2016 to get a value for R_{PE} and initial estimates for V_{PE} and α_{PE}. Then, keeping R_{PE} fixed, α_{PE} is matched to the outer slope for a galaxy with $R_{\rm HI}$ from (Dutton et al. 2019). Finally, V_{PE} is normalized such that

$$V_{rot}(R_{\rm HI}) = V_{\rm HI} \ . \tag{6}$$

These scaling relations only apply for a specific range of masses. As such the 'make_' programs only work for a mass range of $10^{7.5}\ {\rm M_\odot} \leqslant M_{\rm HI} \leqslant 10^{10.5}\ {\rm M_\odot}$.

3 TILTED RING MODELS

The scaling relations described in Sec. 2 uniquely determine the rotation curve and surface density of a galaxy given its HI mass. These profiles must be converted into a tilted ring model in order to produce a mock cube with MCG. This requires a number of observational parameters.

For the 'make_' programs, the second most important parameter is the observed diameter of the galaxy, D (the most important is the HI mass). The diameter of the galaxy sets the distance to object such the projection of $R_{\rm HI}$ on the sky is half of D. To be very clear, the observed face on surface density will be 1 $M_{\odot}$ pc^{-2} at $D/2$ from the observed center of the galaxy.

From Table 1 in the MCG Guide document, there are another five geometric parameters necessary for a tilted ring model. These are the observed center, inclination, position angle, and systemic velocity. The 'make_' programs generate flat disk models where these parameters are kept constant across all the rings. Therefore the user simply needs to specify values for each of these parameters (see Sec. 4 for details).

The remaining tilted ring parameters are V_{disp}, V_{rad}, V_{vert}, dv/dz, z_0, and $z_{gradient}$. As the 'make_' are meant to be simple, axisymmetric models, both V_{vert} and dv/dz are set to zero. By default V_{rad} is also set to zero, but it is possible to set a uniform radial flow for an object.

The user specifies a value for V_{disp} (which is also constant across all radii, which is used to get z_0 and $z_{gradient}$. For simplicity, $z_{gradient} = 5z_0$, while z_0 is derived from the Eq. 7 of (Puche et al. 1992):

$$z_G(R) = \frac{v_{disp}}{\sqrt{4\pi G\rho(R)}}~. \tag{7}$$

Puche et al. 1992 uses a Gaussian scale height while MCG assumes a sech^2 vertical profile so $z_0 = 0.9333 z_G$. The ρ term is the total local density (not just the HI density). We get this term using a spherical approximation for the total mass. While this is certainly not true, it is sufficiently accurate given the resolution limits for galaxies generated using the 'make_' programs (see Sec. 4 for details).

There is one other major parameter to discuss when converting profiles into tilted ring models. That is the importance of the beam size, B. The galaxy diameter D is defined in terms of the number of beams, $D = NB$, where B is the Gaussian full-width-half-max of the major axis of the beam in arcseconds. Additionally, the 'make_' programs set there to be 5 rings per beam. It is also worth noting that the full extent of the tilted ring model is set to $R_{final} = 0.75D = 1.5R_{\rm HI}$.

The 'make_' programs are focused on making low to medium resolution mock observations of realistic galaxies. To that end, D is limited to be between $2 - 50$ B. Similarly, the velocity dispersion is limited to $0 - 20$ km s^{-1}.

To summarize the 'make_' programs construct tilted ring models by first constructing a radial array in arcseconds based on the beamsize and D. These values are converted to kiloparsecs using the distance and fed into Eqs. 2-3 to get the surface density and rotational velocity tilted ring parameters. The geometric parameters are set by the user, along with the velocity dispersion. The velocity dispersion is used along with the rotation curve to get the disk thickness parameters (z_0 and $z_{gradient}$), while the other parameters are set to zero for simplicity.

4 USAGE

Using the 'make_' programs is relatively straightforward. There are two required input files for both MAKE_GALAXY and MAKE_SUITE, as well as a third optional input file for both programs. These input files must be located in the *Inputs* folder. The required MAKE_GALAXY input files are

- **galaxyconfig_MCG.py** ,
- **observatoryconfig_MCG.py** .

MAKE_SUITE also requires **observatoryconfig_MCG.py**, but, instead of **galaxyconfig_MCG.py**, it uses **suite_config_MCG.py**. However, **galaxyconfig_MCG.py** is very similar to **suite_config_MCG.py**.

Assuming that these files exist, the programss can be run from the terminal via

- *python make_galaxy_MCG.py*
- *python make_suite_MCG.py*

The **galaxyconfig_MCG.py** and **suite_config_MCG.py** files describe the general galaxy properties while the **observatory_config_MCG.py** contains the parameters that define the observations. Figure 1 shows an example of the **observatory_config_MCG.py**. This file defines dimensions of the mock data cube, the size of the beam, and the underlying noise. One thing to note in this file is that the cube size is not specified. This is because the default behaviour of the 'make_' programs is to define the cube size in terms of the object diameter and rotation curve.

The main input file for MAKE_GALAXY is **galaxyconfig_MCG.py**. Figure 2 shows an example of one of these files. The first set of inputs describe the observed galaxy. The second set of inputs set the outputs of **make_galaxy**. The final input, *BetaConfigFile*, does not need to be set. It points to the third optional configuration file.

The main input file for MAKE_SUITE, **suite_config_MCG.py**, is nearly identical to **galaxyconfig_MCG.py**. Figure 3 shows an example of this file. The main differences are that the galaxy parameters are now arrays, and there are a few new parameters. MAKE_SUITE produces a number of models for each unique combination of parameters equal to *NumRealizations*. In the example file, there is only one realization per set of parameters, but this can be much larger. The reason this may be necessary is to explore the effect of noise on the observations. In addition, MAKE_SUITE generates models in parallel, so the number of processors to be used must be specified.

A number of the tilted ring parameters discussed in Sec. 3, along with a variety of possible modelling options are not set in these configuration files. Many of these can be set using the beta configuration file. An example of such a file is shown in Fig. 4. Unlike the other configuration files, it is not necessary to set any of these optional parameters.

The first two beta parameters affect the particle density used in MCG. The third parameter, *ranseed*, changes the random seed used for generating the particles in MCG. The next two parameters set the number of points in the profile calculation and the radial extent of the profiles. The next five parameters adjust the default tilted ring parameters from zero.

The final set of beta parameters affect the MCG data cubes. *cube_shape* sets final cube shape rather than using the 'make_' programs calculated shape. The *Beam_Flattening* and *Beam_PositionAngle* parameters allow for non-circular beams. However, it is important to note that this feature is not fully implemented and will lead to incorrect noise calculations. The *nsigma* parameters controls the size of the beam kernel calculated, while the *velocity_smooth_switch* and *velocity_smooth_sigma* parameters determine whether the resulting data cube will be velocity smoothed, and if so, by how much.

```
###          DATA CUBE PARAMETERS
# Cube Dimensions (arcsec, arcsec, km/s)
# Pixel size (arcsec)
PixelSize=6.
# Channel size (km/s)
ChannelSize=4.
# beam FWHM (arcsec)
beam_fwhm=30
#### Underlying Noise amount (mJy/beam)
noise_value=1.6
```

Figure 1. An example observatory configuration file.

5 OUTPUTS

The 'make_' programs produce a number of outputs beyond just the MCG cubes. Before discussing these, it is worth noting the file naming convention. Firstly, each galaxy will be produced will be placed in a subdirectory of the parent directory given by the *OutFolder* parameter. The subfolder and cubes are named according to the galaxy parameters. The naming scheme is *ba_#.mass_#.inc_#.pa_#.veldisp_#* for MAKE_GALAXY and *ba_#.mass_#.inc_#.pa_#.veldisp_#.version_#* for MAKE_SUITE. In this naming scheme, *ba_#* is the beams across the object (D), *mass_#* is the logarithmic HI mass, *inc_#* is the inclination, *pa_#* is the position angle, and *veldisp_#* is the velocity dispersion. For MAKE_SUITE, the *version_#* is the realisation of that specific combination of parameters.

This naming convention is carried over to every file in the output directory. Regardless of the flags, the 'make_' programs will always produce all three possible MCG cubes. They will also always produce a text file with the suffix *Profile* that lists the key input parameters, the calculated parameters that are used in the scaling relations, and the resulting surface density and rotation curve profiles.

If the *PlotVerbose* flag is true, the 'make_' programs will also make two diagnostic plots. The first, named *Name_Profiles.png* shows the galaxy's rotation curve and surface density profiles. Figure 5 shows a sample plot. The second plot made, *Name_MomentMaps.png*, shows the galaxy moment maps, PV diagrams, and velocity profile. Figure 6 shows an example of one of these plots.

If the *FileVerbose* flag is true, the three required MCG input files will also be stored in the output directory. This allows for rechecking whether the MCG cubes have been correctly generated from the tilted ring parameters.

The MAKE_SUITE program also produces catalogue files in two distinct formats, a simple text file, and an SQL file for entry into a database. These catalogue files contain the ID and name of each object as well as all the scalar parameters that go into generating the tilted ring parameters (i.e. $M_{\rm HI}$, $R_{\rm HI}$, D, etc.).

REFERENCES

Spekkens, K., Lewis, C., Deg, N., 2020, in prep

```
# HI Mass of galaxy (logarithmic)
Mass = 8
# Number of beams across DHI (major axis)
Beams = 5.5
# Inclination in degrees
Inclination = 45.
# Position Angle in degrees
PositionAngle=0.
#   Velocity dispersion in km/s
veldisp=8.

# Output Folder
OutFolder='MakeGalaxy_MGC_TestOutput'
# Verbose plot switch
PlotVerbose=True
# Verbose file Switch
FileVerbose=True
#   Beta Configuration Options
BetaConfigFile="Inputs.beta_config"
```

Figure 2. An example **galaxyconfig_MCG.py** configuration file.

```
#   Target HI Masses
Masses=[7.5,8.5,9.5,10.5]
#   Target Beams Across
Beams=[5.5]
#   Inclination selections (degrees)
Inclinations=[45]
#   Position Angle Selections (degrees)
PositionAngles=[0.]
#   Velocity Dispersion Selections (km/s)
veldisps=[8.]
# Number of Realizations/object
NumRealizations=1

n_Processors=4

# Output Folder
OutFolder='MakeSuite_TestOutput'
# Verbose plot switch
PlotVerbose=True
# Verbose file Switch
FileVerbose=False
#   Beta Configuration Options
BetaConfigFile="Inputs.beta_config"
```

Figure 3. An example **suite_config_MCG.py** configuration file.

```
###          TILTED RING MODE PARAMETERS  -- will overwrite the default values
# Cloud mode
cmode = 0
# Base number density of particle clouds
CloudSurfDens = 1000
# random seed for the particle generation
ranseed=-5


####         PROFILES PARAMETERS  -- will overwrite the default values
nBinsPerRHI=100.
limR_RHI=1.


####         ADDITIONAL TILTED RING MODEL PARAMTERS
# x center (degrees)
RA=277.67543
# y center (degrees)
DEC=73.434828
# systemic velocity (km/s)
vsys=1403.93164636
# radial velocity (km/s)
vrad=0.
# derivative of the radial velocity as a function of height above zgradient height
dvdz=0.



###          DATA CUBE PARAMETERS
# Cube Shape  -- can overwrite the calculated cube shape
cube_shape=[200,200,200]
#   Beam flattening (relative to the FWHM defined in observatory_config.py)
Beam_Flattening=1.
#   Beam angle (in degrees)
Beam_PositionAngle=0.
# number of sigma lengths to use for beam smoothing -- overwrites default value of 5
nSigma=5.
# Switch for velocity smoothing (0=none, 1=Gaussian) [default is 0]
velocity_smooth_switch=0
# Width for the velocity smoothing if being used  (km/s) [default is channel width]
velocity_smooth_sigma=4.

```

Figure 4. An example beta configuration file.

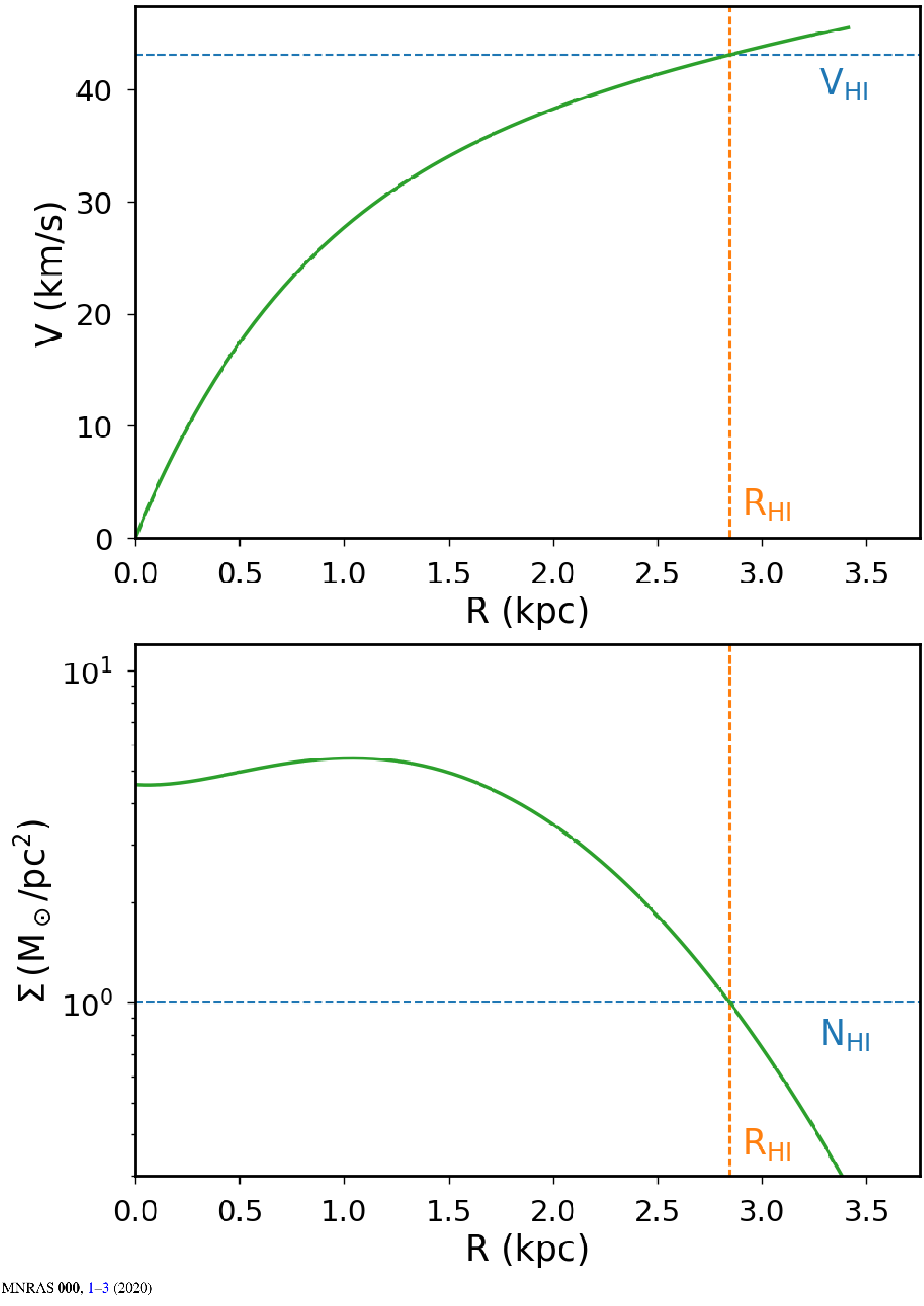

Figure 5. An example of the profiles diagnostic plot.

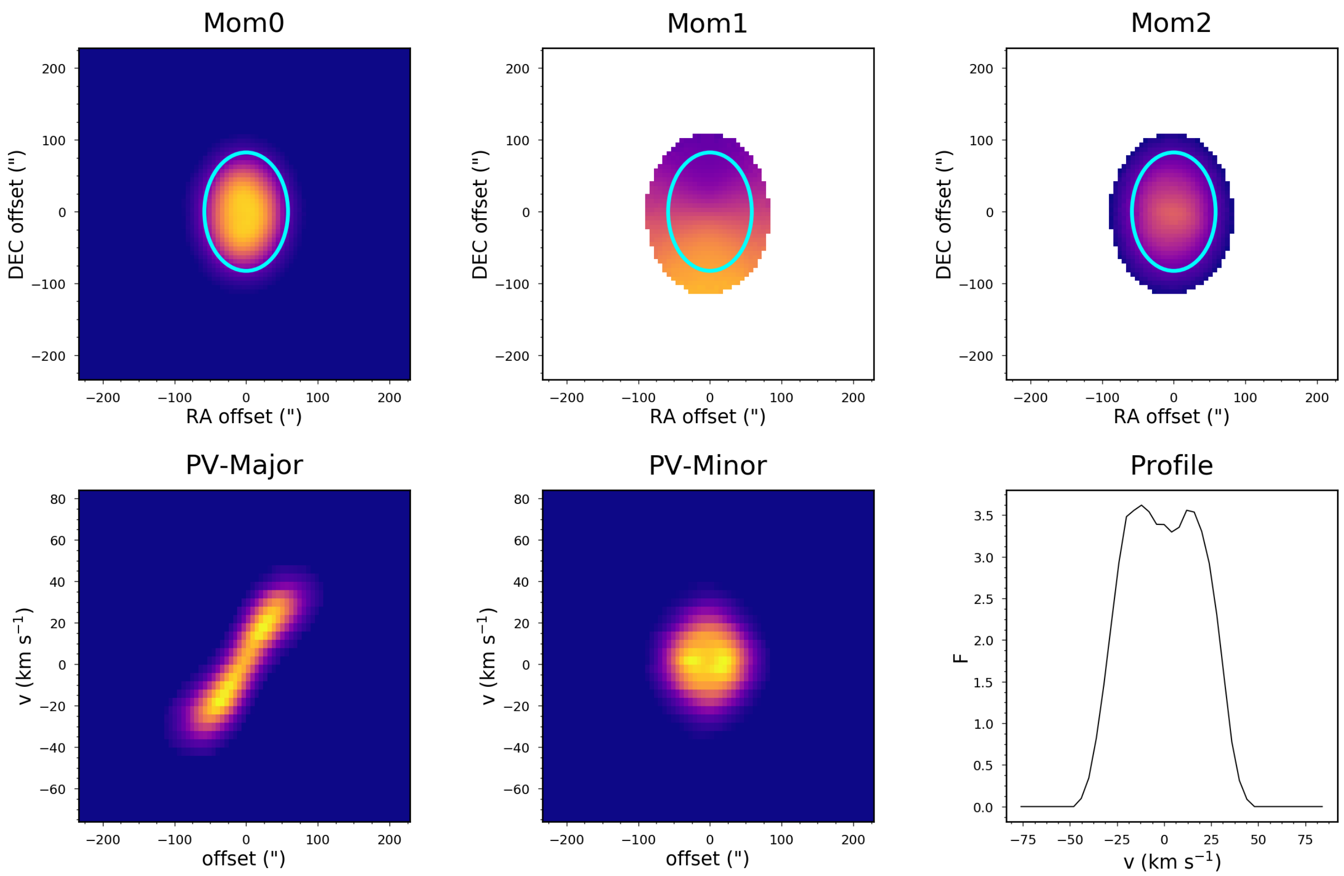

Figure 6. An example of the moment maps diagnostic plot.