# Extracting rotation curve of a galaxy using tilted ring modeling

Astronomy Lab II experiment

## 1 Objective

1. Extract the rotation curve of a galaxy using HI spectral cube
2. Estimate $V_{max}$ and $R_{max}$ by fitting a Brandt profile to the rotation curve
3. Estimate the kinematic parameters of the galactic disk.

## 2 Tools and data required

1. 3D BAROLO Software tool
2. High quality HI spectral cube (interferometric observation)
3. Fitting routine

## 3 Overview

A galaxy is a gravitationally bound system consisting of stars, gas, dust, etc. Each galaxy is known to be hosted by a dark matter halo. By mass, this is the most dominant component. It contributes $\sim 90\%$ of the total mass. Different constituents of galaxies settle on a disk, which rotates around the galaxy center. This rotation resists the collapse of all materials towards the center under gravity. Observationally it is found that different parts of a galaxy rotate with different angular speeds. This kind of rotation is called *'differential rotation'*.

Estimating this rotation speed as a function of radius and other kinematical parameters (e.g., position angle, inclination, systemic velocity, etc.) is crucial in many aspects. For example, the amount of gravitating matter inside a radius, the dark matter distribution, galaxy inclination, gas outflow, infall, etc., can be determined by examining the kinematics of a galaxy. Hence, observationally determining the kinematics of a galaxy is critical.

Resolved spectroscopic observations can be used to estimate the kinematics of a galaxy. In this regard, observations of Neutral Hydrogen (HI) play a significant role. The HI-21 cm emission is a line emission originating due to spin-flip transition. In the excited state, the spin of the electron and the proton is parallel. When this parallel spins transition to an anti-parallel state, radiation of frequency 1420.4 MHz is emitted. Because this is a line emission, the rest-frame frequency of this transition is fixed with a minimal natural broadening in common astrophysical conditions. Now, if an HI cloud rotates, the central line frequency suffers a Doppler shift, which could be detected using sensitive spectrometers. The frequency 1420.4 MHz can be observed with radio telescopes from ground-based observatories (e.g., VLA, GMRT, MeerKAT).

Modern-day synthesis radio telescopes can perform resolved spectroscopic observations with adequate sensitivity and resolution. It can measure HI spectra from individual galaxy parts producing a spectral cube. This spectral cube contains the resolved kinematic information of the galaxy and can be used to estimate the same using sophisticated software tools (e.g., 3D BAROLO).

## 4 The tilted ring modeling

Though traditionally, in an ideal disk galaxy, it is assumed that the gas and stars rotate in a planar thin disk, observations show that the disk is far from a simple plane. Most of the time, it shows deformity, especially at the outskirts of the galactic disk. These deformities lead to different kinematic parameters for different galaxy parts. Hence, to estimate the kinematic parameters of a galaxy, one must consider different parts individually. To do that, modern kinematic routines consider the galaxy to be made up of concentric rings characterized by different kinematic parameters, i.e., centers, rotation velocities, position angle, and inclination. This is illustrated in Fig. 1. As can be seen, the galaxy is considered to be a collection of ‘tilted rings’ having different kinematic parameters.

The kinematic parameters of each ring are optimized separately by the *‘tilted ring’* model-fitting routines. The ring parameters are fitted in each iteration, and model spectral cubes or velocity fields are produced. These are then compared with the observed one to update the kinematic parameters in the next iteration. This process continues till convergence is achieved (see Jozsa et al. 2015 and Di Teodoro & Fraternali 2015 for more details). At the end of the fitting, different parameters, e.g., rotation velocity, inclination, PA, etc., are obtained as a function of radius. These parameters then further can be used for different science cases, e.g., estimating dark matter distribution, dynamical modeling, estimating vertical structure, etc.

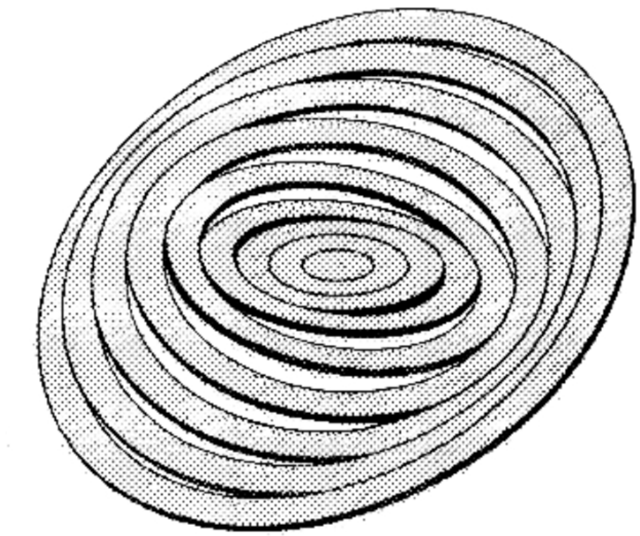

Figure 1: Schematic of model tilted rings in a galaxy for kinematic modeling.

# 5 Setup and method

We will be using the software 3D-BAROLO (Di Teodoro & Fraternali 2015) to estimate the rotation curve of a galaxy using HI data.

## 5.1 Installing 3D BAROLO

Try a binary installation if it doesn’t work then compile the source code.
The installation instruction can be found here

1. First, install the pre-requisites. The command shown here is for Debian-Ubuntu OS.

   - CFITSIO

     ```
     > sudo apt update
     > sudo apt install libcfitsio-dev
     ```

   - FFTW3

     ```
     > sudo apt update
     > sudo apt install fftw3-dev
     ```

   - WCS Library

> sudo apt update

> sudo apt install wcslib-dev

- Qt

  > sudo apt-get install build-essential

  > sudo apt install qt5-default

- GNU Plot

  > sudo apt install gnuplot

2. Then compile and install the package

   – Download the source code from the Barolo website and unzip the file. This will create a directory. Go inside the directory and run the following commands.

   > ./configure

   > make

   > sudo make install

### 5.2 Running 3D BAROLO

1. The spectral cube will be provided in a fits format file
2. Keep the fits file and the initial parameter file in the same directory
3. Run BAROLO by `BBarolo -p parameter.par` , where parameter.par is the file containing the initial parameters and other optimization settings

## 6 Result and discussion

- Extract the rotation curve of the given galaxy.
- Plot the rotation curve and other kinematic parameters and interprete the results.
- Fit the rotation curve with a Brandt profile and estimate $V_{max}$ and $R_{max}$.
- Discuss the *tilted ring model* fitting.
- What is the difference between 2D and 3D fitting? Which one is better and why?
- Discuss the shortcomings of the *tilted ring modeling*?