Modelling the dynamics of neutral hydrogen (HI) in the interacting galaxy system Arp86

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Abstract

Interacting galaxies are key phenomena for studying how gravity shapes the structure and evolution of galaxies. These systems provide information about gas dynamics, star formation, tidal interactions, and angular momentum redistribution. By analyzing neutral atomic hydrogen (HI), we can directly trace the diffuse gas component of the interstellar medium that responds most strongly to tidal forces. Arp86 is a well-known interacting system composed of three galaxies: the main spiral galaxy NGC 7753, its companion NGC 7752, and a third, smaller member, 2MASX J23470758+2926531. This system exhibits prominent tidal features and strong distortions in both its stellar and gaseous components, making it an excellent case study for exploring the role of interactions in galactic dynamics. In this work, we analyze HI observations of Arp 86 obtained with the APERTIF instrument on the Westerbork Synthesis Radio Telescope (WSRT). We model the dynamics of the HI disks of the galaxies in order to quantify their kinematic properties. Specifically, we use the 3DBarolo software tool, which fits inclined ring models directly to the HI data. This method allows us to reconstruct the large-scale rotation of each disk, while producing diagnostic maps of the intensity, velocity, and velocity dispersion of the HI. From the dynamic gas models for every galaxy in this system, we obtain rotation curves that directly constrain the mass distribution within the galaxies and enable us to compare them with the maps of the observed HI. We subtract the obtained models from the observed data and analyze the residuals, which show gas structures and movements that differ from the organized rotation of the disks, including tidal arms, gas flows between the galaxies and distortions. Investigating these residuals is essential for comprehending the overall dynamic condition of the system, as they reveal the structure of interaction-driven gas that is not accounted for by rotational models. The use of HI observations together with dynamic models can reveal how gas is redistributed during galactic interactions and how this impacts galaxy evolution.

Contents

1 Introduction

When studying the universe, galaxies serve as our primary source of information. By observing them, we can investigate the distribution of gas, stars, and interstellar clouds, which reveal clues about their formation, evolution, and dynamics. Galaxies are classified into different types based on their shape, luminosity, and other physical characteristics. In this study, we focus on spiral galaxies—rotating systems characterized by their nearly circular shape, prominent disks, and distinctive spiral arms.

A key tool for understanding these galaxies is neutral hydrogen (HI), which traces their gas distribution and kinematics. Because HI is abundant and detectable at radio wavelengths, we can use it to measure fundamental properties such as:

- The systemic velocity (the galaxy's bulk motion along the line of sight)
- The radial velocity field (how gas moves within the disk)
- The rotation curve (which reveals the distribution of mass, including dark matter, as a function of distance from the center)

Figure 1: Visible-light image of the inteacting galaxy system Arp86, captured by the ESA Hubble Space Telescope

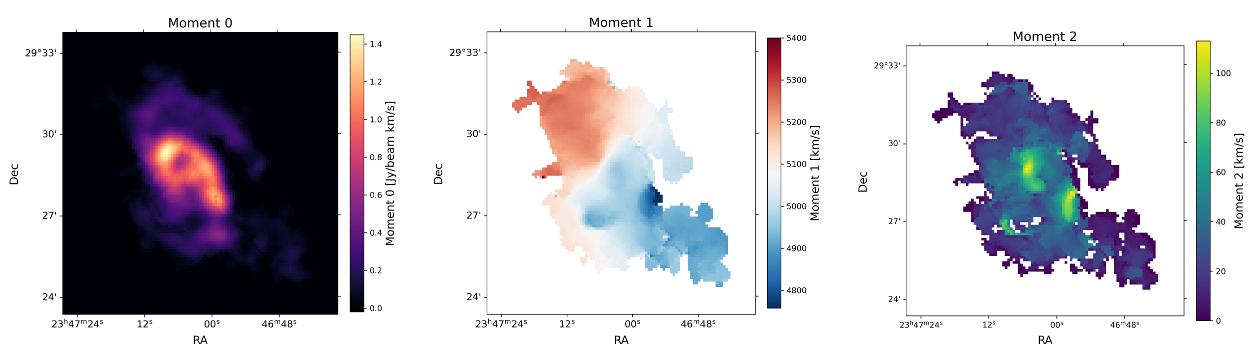
Galaxies are rarely isolated; they often exist in pairs or systems where gravitational interactions dominate. When galaxies come close enough, they may undergo a merger, eventually forming a single, more massive galaxy. The outcome depends on the merger's scale: minor mergers can distort the larger galaxy's structure, while major mergers typically destroy ordered motion, leaving behind an irregular galaxy. By mapping the HI gas in such systems, we can trace how the gas is redistributed during interactions, offering insights into the dynamical processes shaping galaxies.

2 Data and Methods

We used a 3D dimensional data cube of the HI emission in Arp86, obtained with the APERTIF instrument on the Westerbork Synthesis Radio Telescope (WSRT). The data cube has three axes: two spatial dimensions (right ascension and declination) and one spectral dimension or velocity. Each voxel in the cube represents the HI intensity at a specific position and velocity. To explore and visualize the data cube we used DS9 and python. DS9 is an astronomical imaging and data visualization application that allows us to view and analyze FITS files, including 3D data cubes. For a deep a analysis we used Python to inspect the cube, identify features, and create moment maps (integrated intensity, velocity field, and velocity dispersion). We specifically used the following python packages: Astropy, Matplotlib, Numpy, and SpectralCube. Astropy provides tools for handling FITS files and performing astronomical calculations. You can find the code in the github repository. The first step in our data handling was to load the FITS file and look the header information. The header contains metadata about the observation, including the coordinate system, pixel scale, and velocity information. We also inspected the data cube to understand its dimensions and the range of values it contains. You can check the header information of our data here.

3 Galaxy NGC7753

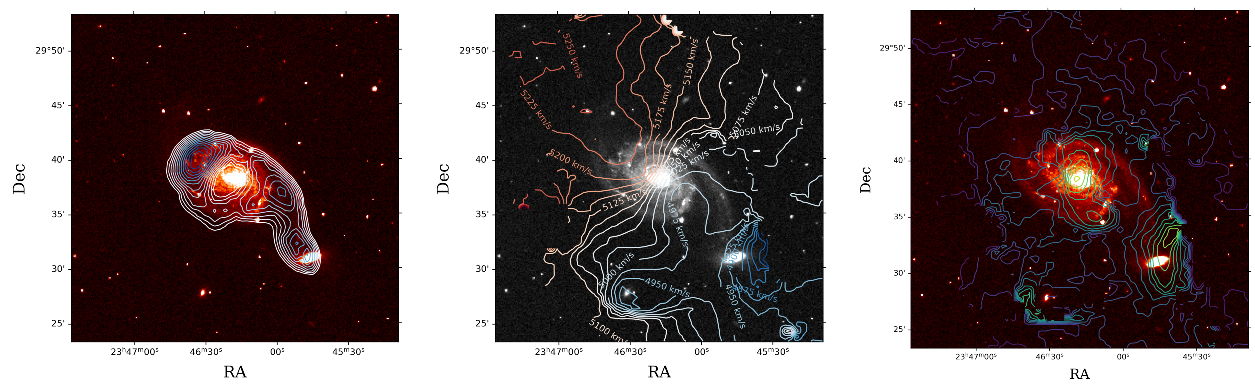
The first analisis we did with python was the throughout the integrated intensity, velocity field, and velocity dispersion of the hole system. The integrated intensity or moment 0 map represents the total HI intensity along the velocity axis. This map allow us to see the distribution of HI gas in the galaxy system. The velocity field or moment 1 map shows the intensity-weighted average velocity of the HI gas at each position. This map reveals how the gas is moving within the galaxy system, indicating rotation and any peculiar motions. We plot this map in red and blues colors to represent gas moving towards us (blueshifted) and away from us (redshifted). The velocity dispersion or moment 2 map indicates the spread of velocities at each position, providing insights into the turbulence and random motions of the gas. Higher velocity dispersion values can indicate regions of active star formation or interactions.



(a) HI intensity (b) Velocity field (c) Velocity dispersion

Figure 2: Integrated Intesity, Velocity field, and velocity dispersion of the galaxy system.

We also did a comparison of the Hi features with an optical image. To do so, we downloaded an extra file, which is the optical image of NGC7753 from the DSS 2 Blue surver. Each moment map was reprojected using countour levels. The overleays were then plotted with consistent celestial coordinates (WCS) and axis labeling (RA, Dec) as before.



(a) HI intensity (b) Velocity field (c) Velocity dispersion

Figure 3: Optical image of Arp 86 overlaid with contours of neutral hydrogen (HI) intensity (left), velocity field (middle), and velocity dispersion (right).

3.1 BBarolo Model

3.1.1 Introduction to BBarolo

BBarolo (Building BArolo Line-profile Observations) is a software package designed for 3D kinematic modeling of emission-line observations, particularly for studies of the neutral hydrogen (HI) distribution in galaxies. The software implements a tilted-ring model approach to derive rotation curves and kinematic parameters from spectral line data cubes. This code works with 3D dimensional FITS data cubes and creates a serie of models as artificial 3D observations, which can be compared directly to the input data cube. Then it finds a set of geometric cinematic parameters that best describe the observed data. **put reference BBarolo paper here**

3.2 Model Setup and Parameters

We performed 3D kinematic modeling of the HI gas using the BBarolo (Building BArolo Line-profile Observations) software package. The modeling process involved creating parameter files (.par) to configure the analysis and running BBarolo on our masked HI data cubes.

3.2.1 Workflow

The typical BBarolo analysis involves:

1. Preparing the input data cube and mask
2. Setting initial parameters (geometry, velocity field)
3. Running the fitting procedure
4. Analyzing the output model and residuals
5. Iteratively refining parameters

3.3 Model Setup and Parameters

We performed 3D kinematic modeling of the HI gas in Arp86 using BBarolo. The modeling process involved creating parameter files (.par) to configure the analysis and running BBarolo on our masked HI data cubes.

The key parameters used in our BBarolo analysis included:

- **Input/Output Configuration**:

- INFILE: `ngc7753_masked.fits` (our masked HI data cube)
- OUTFOLDER: `bbarolo_results/` (directory for output files)
- MASK: `ngc7753_mask.fits` (emission mask)

- **Galaxy Geometry Parameters**:
  - `XPOS, YPOS`: Center coordinates of the galaxy
  - `VSYS`: Systemic velocity (km/s)
  - `PA`: Position angle of the major axis
  - `INCL`: Inclination angle
- **Modeling Parameters**:
  - `RADII`: Radial range for the analysis (e.g., 0 to 120 arcsec in steps of 10 arcsec)
  - `NRADII`: Number of radial rings
  - `VROT`: Initial guess for rotation curve
  - `VRAD`: Radial velocity component
  - `VDISP`: Velocity dispersion
- **Fitting Options**:
  - `FITMODE`: 3D (full cube fitting)
  - `FLAGERROR`: TRUE (estimate uncertainties)
  - `NORM`: TRUE (normalize profiles)

3.3.1 Example of parameters file

The following example is the best parameters we used to model the galaxy with BBarolo.

Table 1: Main input parameters used in the 3DBarolo modeling.

Parameter	**Value**
FITSFILE	S2349+2904_HIcube2_clean_smooth_image_5_cube_kms.fits
THREADS	4
3DFIT	true
RADSEP	5
NRADII	18
VSYS	5009 (fixed)
XPOS	45
YPOS	55
VROT	free
VDISP	free
INC	37
PA	free
MASK	file(S2349+2904_HIcube2_clean_smooth_image_5_mask_kms.fits)
STARTRAD	2

3.3.2 Analysis of BBarolo Model

We obtain different kid of results with BBarolo, in this work we focus on the best fit parameters and the 3D cube model. We make a comparison between the observational data and the model produced with BBarolo and we also compute the residuals. We plot these results in fig.

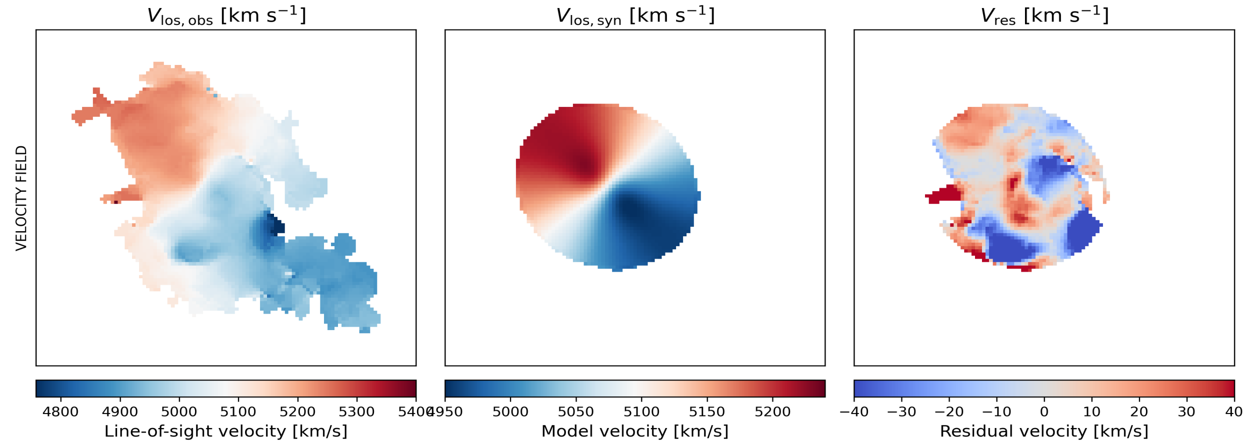
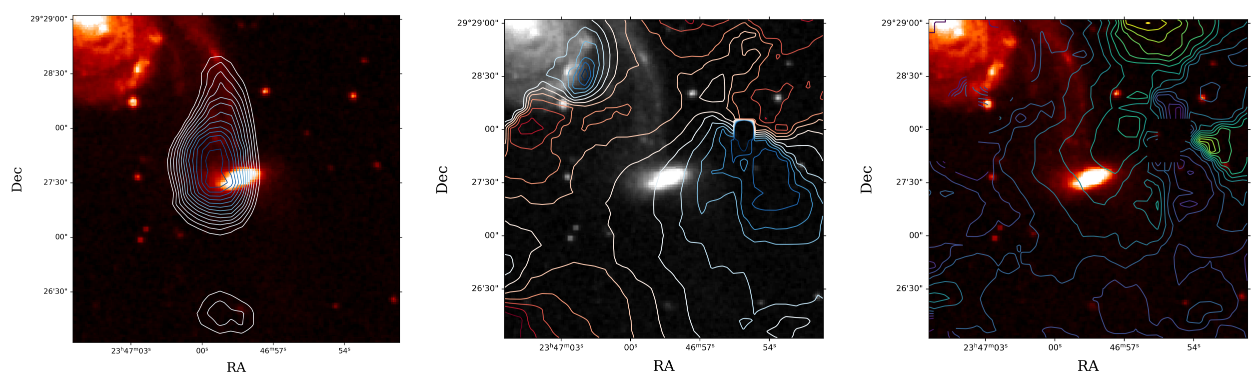


Figure 4: Comparison between the obervational Data and the Barolo Model of NGC7753 along with the residuals.

From the residuals we can extract useful information about what doesn't fit the model, and we identified high intensities in regions were are located the other two galaxies part of the system. BBaralo is only able to model one galaxy, but we are interested to model the other two galaxies also. To do so we proceeded to remove from the original data Cube the data of the BBarolo model, this will eliminate the gas of the big galaxy NGC7753 and left the gas of the other two galaxies. Then we save this new data into a new Cube, we will use this file to fit the other two galaxies separately in the next sections.

4 Galaxy NGC7752

Here we present the result for the NGC7752's model. As before we start analysing the observational data. In fig we plotted the integrated intensity, the velocity field, and velocity dispersion as contour lines over the optical image.



(a) HI intensity

(b) Velocity field

(c) Velocity dispersion

Figure 5: Integrated Intesity, Velocity field, and velocity dispersion of the galaxy system.

4.1 BBarolo Model

We model NGC7753, for this galaxy is kind of difficult to model since the gas is distorted due to the gravitational atraction of NGC7753. There is a lot of gas flow going towards NGC7753, but in the fig we can also notice that ther is gas going down the galaxy in the south direction. We need to read a more about similar systems so that we can discuss about why we are seeing this phenomena, so this part is still being developed...............

4.1.1 Modeling Parameters

We tried differenet models for this galaxy and lot of them ware a failure. We should be cautiousness selecting the mask, and the type of normalization, and in this part te number of ring for fitting is less that the first model of NGC7753, this due to the size of the galaxy and the size of the data cube. The number of rings depend on the radius of the galaxy, and the radius of the galaxy in pixels can be computed using the moment 0 map and the optical image. Here we noticed how important is the overlay of the intensity field with the optical image, here we used that plot to compute the radius of the galaxy. The best modelig parameters for tihs galaxy are:

Table 2: Input parameters used in the 3DBarolo modeling of NGC 7752.

Parameter	**Value**
FITSFILE	ngc7752_cube.fits
THREADS	4
3DFIT	true
RADSEP	5
NRADII	10
VSYS	5009 (fixed, not free)
XPOS	59
YPOS	41
VROT	free
VDISP	free
INC	63.8
PA	free
MASK	SMOOTH&SEARCH
NORM	AZIM

4.1.2 Results and Analysis of BBarolo Model

The resulting BBarolo's Model of NGC7752 is represented in figure. The interesing part we can see it in the residuals, there is lot of gas that is not fitted in the model and it is due to the gas flow going to the big galaxy NGC7753. An interesting thing to analyse would be the amount of gas that is not fitted.

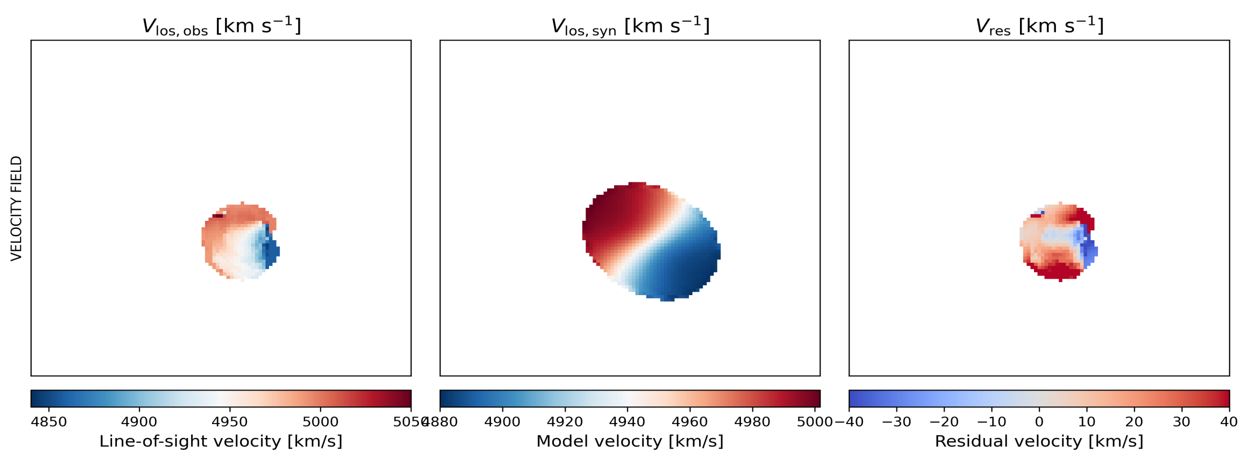
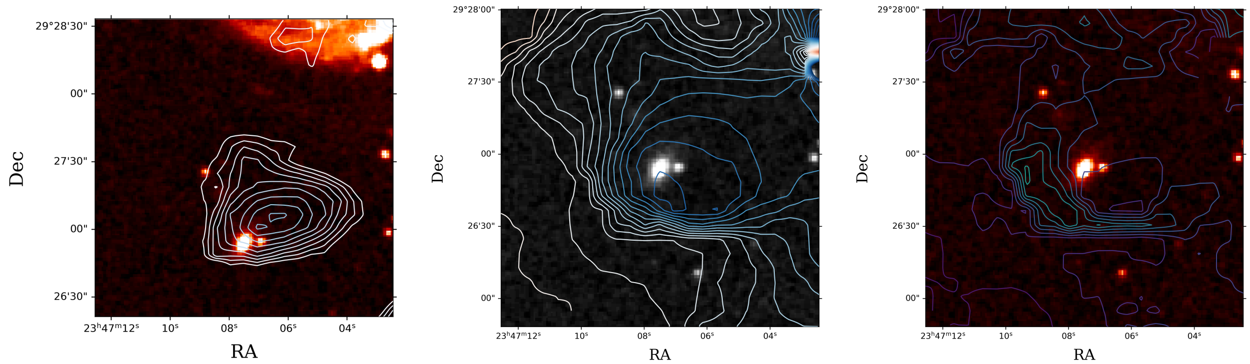


Figure 6: Comparison between the obervational Data and the Barolo Model of NGC7752 along with the residuals.

5 Galaxy 2MASX J23470758+2926531

Here we present the result for the galaxy 2MASX J23470758+2926531's model. We need to observe the countour lines of the integrated intensity, velocity field, and velocity dispersion to see how the gass is distributed and moving within the galaxy. At fist sight this kin of analysis is useful for later compute the modeling parameters for this galaxy for instance the galaxy radius and central position of the galaxy.



(a) HI intensity (b) Velocity field (c) Velocity dispersion

Figure 7: Integrated Intesity, Velocity field, and velocity dispersion of the galaxy system.

5.1 BBarolo Model

The model of this galaxy was a challenge, since is it very small and was kind of difficult to find the best parameters fo modeling with BBarolo. The essential parameters that allow us to fit with BBarolo was the number of rings. After finding the radius of the galaxy we should specify to BBarolo how many number of rings use to fit the data. In this case the number of rings were 10, it is small but BBarolo can handle a good model with this number of rings. Another important parameter was the mask for the data, here we used the cube mask () and the model improved a lot.

5.1.1 Modeling Parameters

Table 3: Input parameters used in the 3DBarolo modeling of the third galaxy in Arp 86 (2MASX J23470758+2926531).

Parameter	Value
FITSFILE	arp86-3_cube.fits
THREADS	4
3DFIT	true
RADSEP	5
NRADII	6
VSYS	5009 (fixed, not free)
XPOS	41
YPOS	37
VROT	free
VDISP	free
INC	70
PA	not free
MASK	file(S2349+2904_HIcube2_clean_smooth_image_5_mask_kms.fits)
NORM	AZIM

5.1.2 Results and Analysis of BBarolo Model

The resulting BBarolo's Model of 2MASX J23470758+2926531 is represented in figure. The interesing part we can see it in the residuals, there is lot of gas that is not fitted in the model and it is due to the gas flow going to the big galaxy NGC7753. An interesting thing to analyse would be the amount of gas that is not fitted. In fact, in the next section we will try to compute the amount of gas that is not fitted in the three galaxies, this will give us an idea of how much gas is being transfered from one galaxy to another.

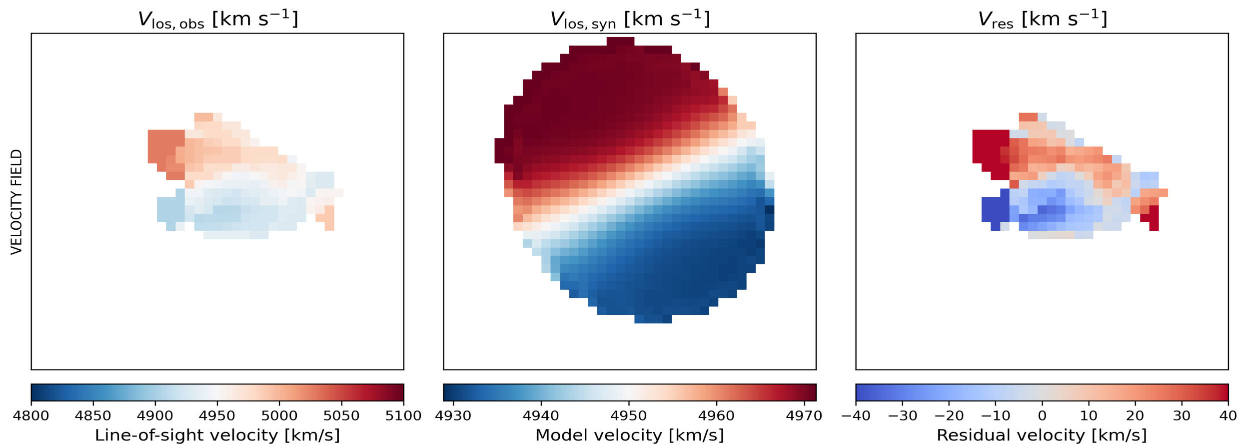


Figure 8: Comparison between the obervational Data and the Barolo Model of 2MASX J23470758+2926531 along with the residuals.

6 Residuals

After modeling the three galaxies in the system Arp86, we proceed to compute the amount of gas that is not fitted by the models. To do so we use the residuals that we obtained from each model. The residuals are obtained by subtracting the BBarolo model from the observational data. The resulting cube contains only the gas that is not fitted by the model, this gas can be due to gas flows between the galaxies or tidal interactions.

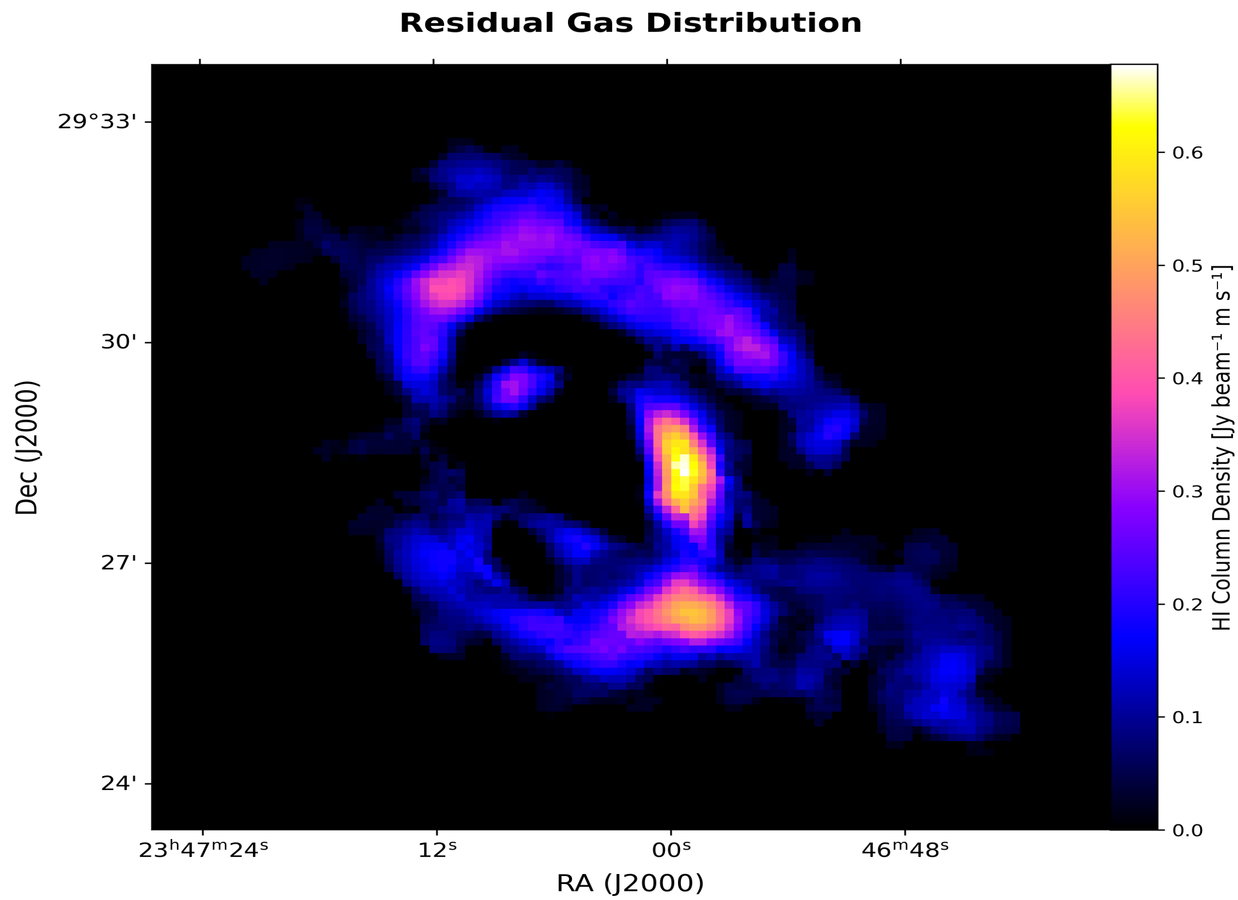


Figure 9: Residuals of the three galaxies in the system Arp86.

6.1 Kinematic Modelling of the System

Here we show the observed data, the BBarolo model of each galaxy, and the residuals. The model of NGC7753 has red contours lineas, NGC7752 has yellow contour lines, and 2MASX J23470758+2926531 has orange contour lines. The residuals show the gas that is not fitted by the models. We can clearly see the gas that is not fitted by the models,this gas is due to the interactions between the galaxies. The gas flows from NGC7752 to NGC7753 are clearly visible in the residuals. Each figure is plotted at different velocity channels, so we can clearly see at which velocites the gas belonging to each galaxy is located. The big galaxy (NGC7753) is moving at higher velocites, while the small galaxies are moving at lower velocities. We expect this behavior since the big galaxy has higher mass and therefore higher gravitational potential. We can see that approximately at 4910 km/s the model of 2MASX J23470758+2926531 dissapears but there still gas in that location, so that could mean that the model is still not perfect.

7 Conclusion

In this work, we have presented a kinematic model of the system Arp86 using HI observations obtained with the APERTIF instrument on the WSRT. We used the BBarolo software to model the dynamics of each galaxy in the system, obtaining rotation curves and kinematic parameters. The residuals from the models revealed gas flows and tidal interactions between the galaxies, providing insights into the dynamical processes shaping this interacting system. For future work, we plan to analyze the mass distribution within each galaxy using the rotation curves obtained from the BBarolo models. We succeeded in modeling the three galaxies separately and get the kinematic parameters for each one. We expect that this procedure will

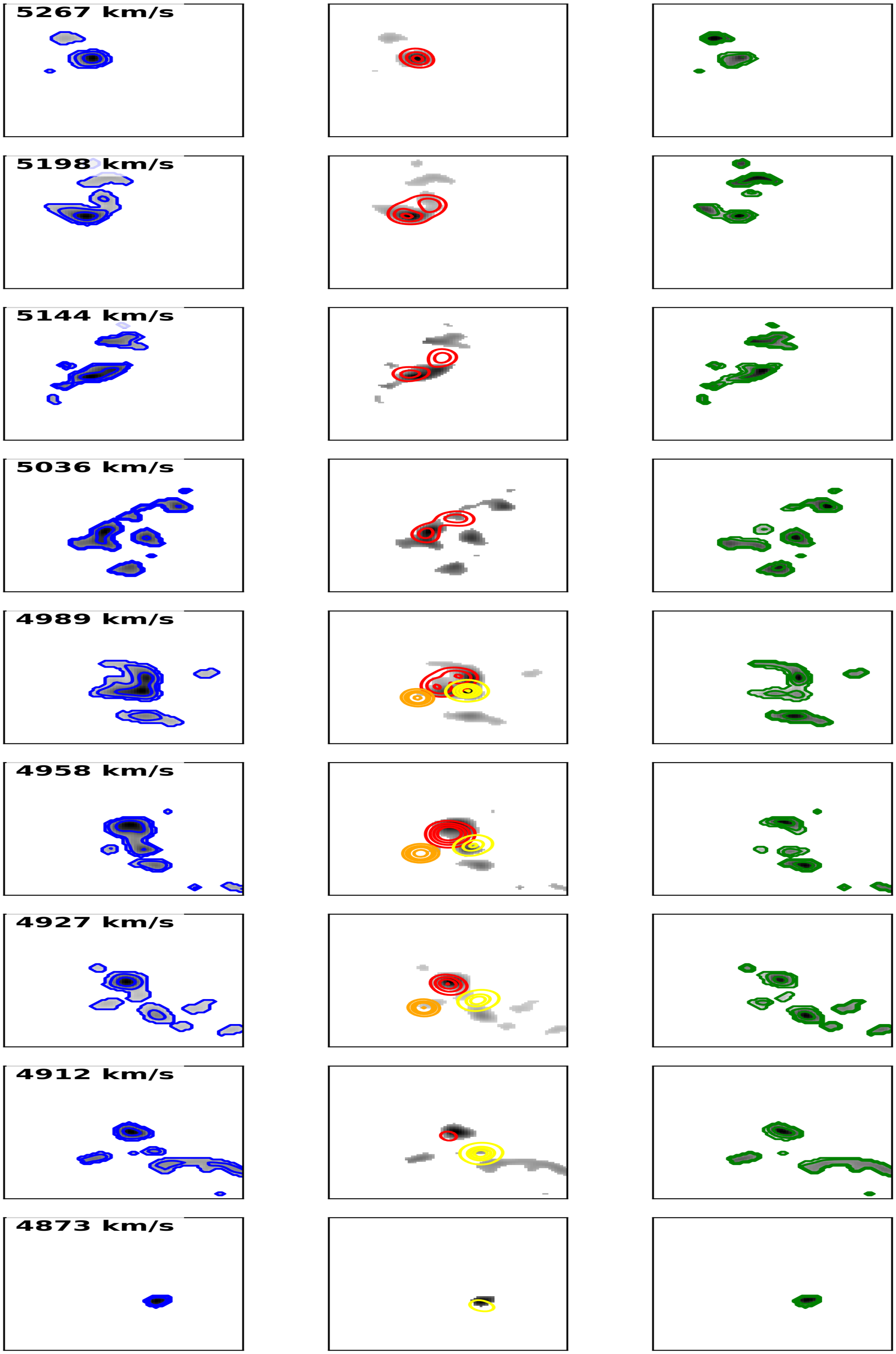


Figure 10: Comparison between observations of Arp86 (left) with the rotating BBarolo models (centre) and residuals (right)

also work for other interacting systems observed with APERTIF, allowing us to study the dynamics of gas in a variety of galactic environments.