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 (spiral, elliptical, and irregular) based on their shape, luminosity, and other physical characteristics (Rai 2010). In this study, we focus on spiral galaxies whihc are 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) (Giovanelli and Haynes 1988)

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 and 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 (Barnes and Hernquist 1992). 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 Observational Data

The data used for this research was obtained with the APERTIF instrument on the Westerbork Synthesis Radio Telescope (WSRT). The sample consists of a three-dimensional data cube of the HI emission in the interacting galaxy system Arp86. This system is located at 106.5099 -31.3384 [60200 60200 90] degrees (Gal coord,ep=2000). This system consists of three galaxies: the big spiral galaxy NGC7753, its companion NGC7752, and a third smaller member 2MASX J23470758+2926531. The data cube has three axes: two spatial dimensions (right ascension RA and declination Dec) and one velocity (m/s) dimension. The units of the data are in Jy/beam, which represent the flux density per beam area. More information of the data header is available on github/AnyelTars. The optical image of the system is shown in Figure 1. Moment maps of the HI emission of the system are shown in Figure 2.

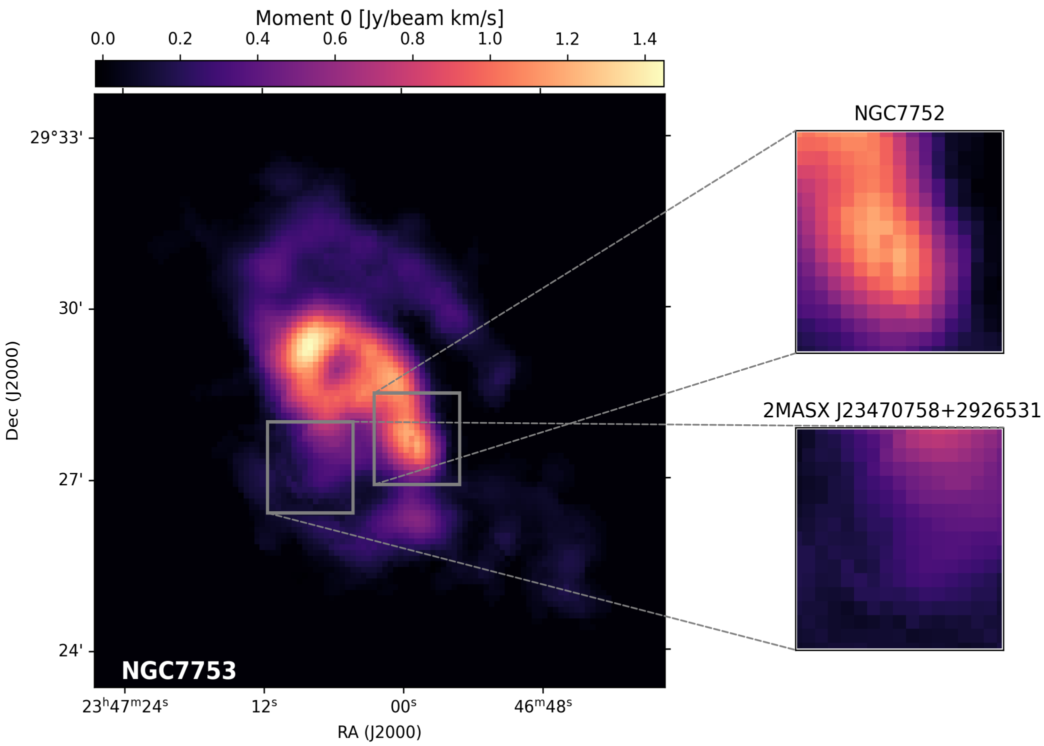


Figure 2: Integrated intensity (moment 0) map of the HI emission in Arp86, showing the distribution of neutral hydrogen gas across the system.

3 Methods

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.

3.1 3D Kinematic Modeling with 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. (Teodoro and Fraternali 2015)

3.1.1 Model Setup

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.

3.1.2 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

3.1.3 Parameters

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)

3.1.4 Initial Parameters NGC7753

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

3.1.5 Initial Parameters NGC7752

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

3.1.6 Initial Parameters 2MASX J23470758+2926531

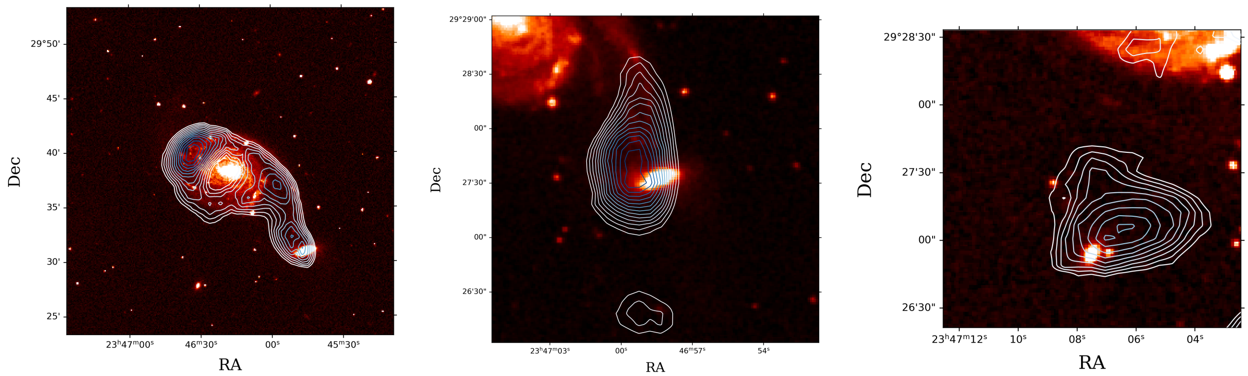
Table 3: Input parameters used in the 3DBarolo modeling of the third galaxy in Arp 86 (2MASX J23470758+2926531).

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

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: For modeling 2MASX J23470758+2926531 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.

4 Results

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) NGC7753 (b) NGC7752 (c) 2MASX J23470758+2926531

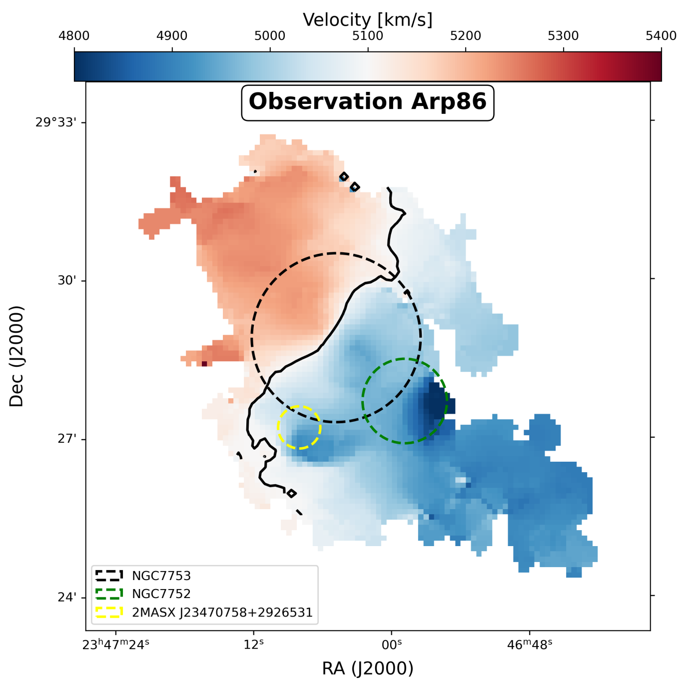
Figure 3: Optical image of Arp 86 overlaid with contours of neutral hydrogen (HI).

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.

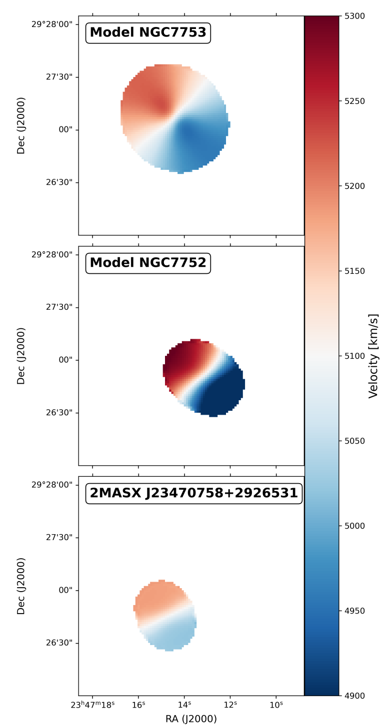
4.0.1 Analysis of BBarolo Model

In this section we present the results of the BBarolo modeling for the three galaxies in the Arp86 system. The velocity filed of the system along with the BBarolo's velocity field for each galaxy are shown in figure 4. In figure 4a each galaxy is enclosed by a dotted circle with different colors for better visualization. Each circle were located in the center of each galaxy according to pixel coordinates and the radius were selected according to the size of each galaxy in the moment 0 map. The gas of the entire systems is moving between approximately 4800 km/s to 5400 km/s. The big galaxy NGC7753 is moving at higher velocities (approximately 5000 km/s to 5200 km/s). Quite the opposite is true for the small companion NGC7752, which is moving at velocities (approximately 4900 km/s to 5300 km/s). The third galaxy 2MASX J23470758+2926531 is moving at different velocities compared the other two (approximately 5000 km/s to 5100 km/s). This behavior is expected since the big galaxy has higher mass and therefore higher gravitational potential, but NGC7752 has interesting behaviors in its velocity field due to the interactions with NGC7753.

A plot comparing the observational data, BBarolo models, and residuals for each galaxy is shown in figure 5. The residuals show the gas that is not fitted by the models, indicating gas flows and tidal interactions within the system.

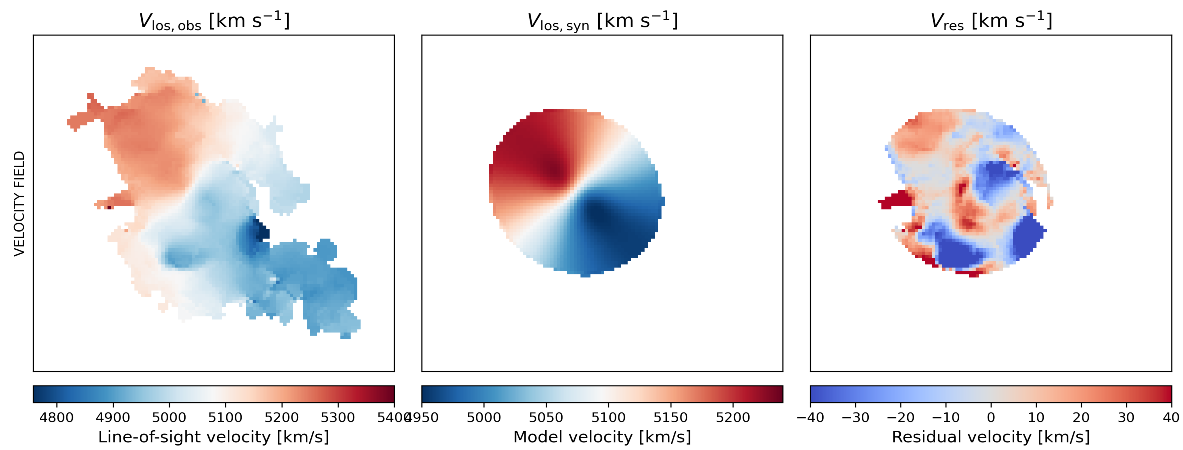


(a) Velocity field observation

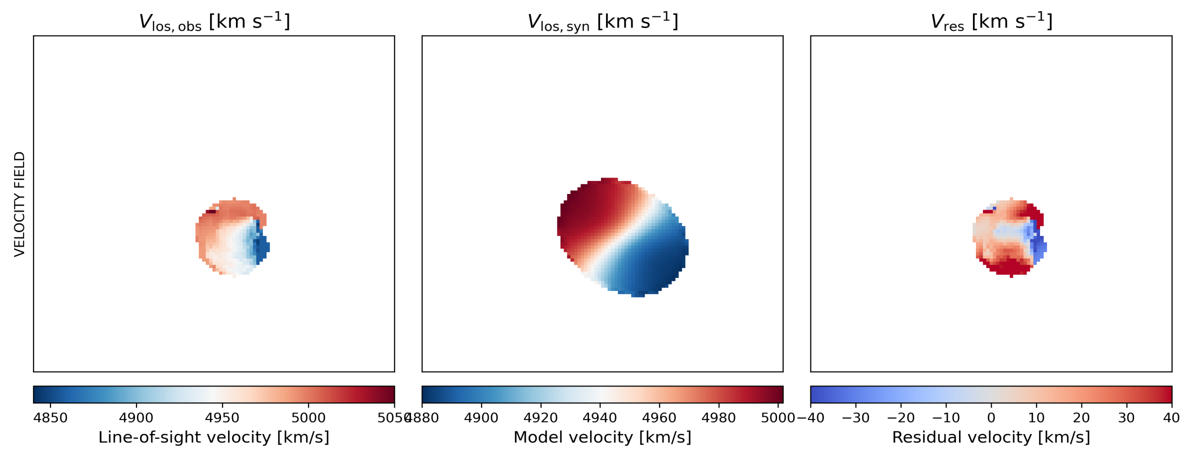


(b) Velocity field models

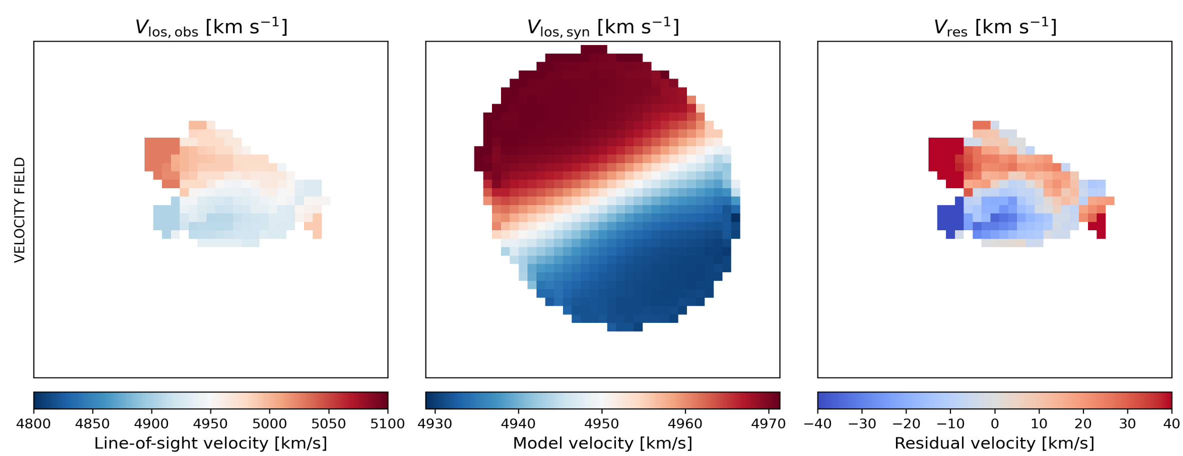
Figure 4: (a) Velocity field of the Arp86 system from observations. (b) Velocity field models for each galaxy in the system: NGC7753 (red), NGC7752 (green), and 2MASX J23470758+2926531 (blue). Each galaxy is enclosed by a dotted circle for clarity.



(a) NGC7753: Comparison between observational data, Barolo model, and residuals.



(b) NGC7752: Comparison between observational data, Barolo model, and residuals.

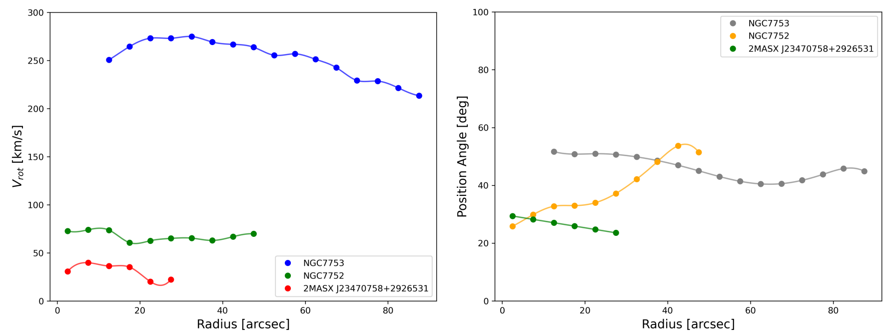


(c) 2MASX J23470758+2926531: Comparison between observational data, Barolo model, and residuals.

Figure 5: Comparison between the observational data, BBarolo models, and residuals for the three galaxies in Arp86.

4.0.2 Rotation Curves

Figure 6 shows the best-fit HI rotation curves and position angles as a function of radius for each galaxy. The rotation curves reach velocities from approximately 40 km/s to 270 km/s. Successful fits were obtained for 16, 10,and 6 rings for NGC7753, NGC7752, and 2MASX J23470758+2926531 respectively. The position angles vary with radius, indicating warps or disturbances in the disks due to interactions.



(a) Rotation curves of the three galaxies in Arp86

(b) Position angles of the three galaxies in Arp86

Figure 6: HI rotation curves (a) and position angles (b) as a function of radius.

4.1 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.

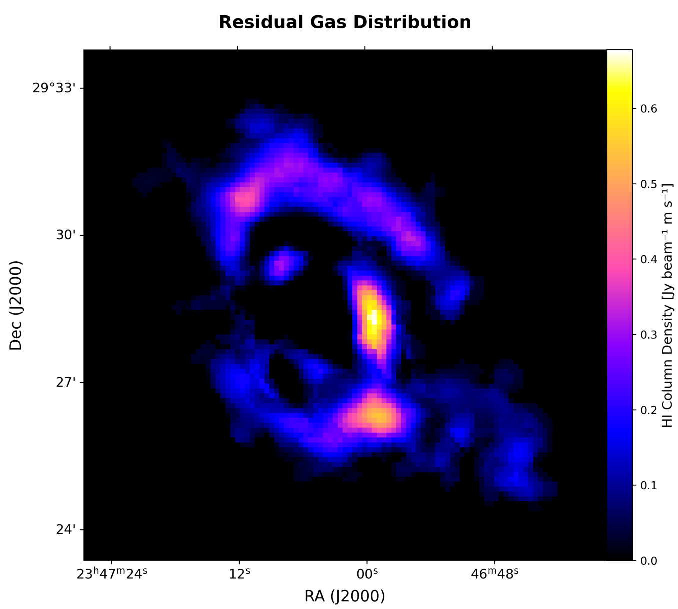


Figure 7

4.2 Kinematic Modelling of the System

Figure 8 shows the BBarolo model of each galaxy, and the residuals. The model of NGC7753 has red contours lines, 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.

5 Discussion

5.1 Reliability of the models

HI rotation curves of the three galaxies exhibit a typical behavior of a spiral galaxy, with a slightly rising inner region followed by a flattening at larger radii (Figure 6). This pattern is consistent with the presence of a massive dark halo surrounding a spiral disk (Sofue and Rubin 2001). The maximum rotation velocities reached are approximately 270 km/s for NGC7753, 120 km/s for NGC7752, and 80 km/s for 2MASX J23470758+2926531, reflecting their relative masses and sizes.

The position angle variations with radius (Figure 6.b) show significant deviations from constant values, particularly for NGC7752 and the companion galaxy. These variations are indicative of warped or disturbed disks, a common feature in interacting systems where tidal forces perturb the regular rotation pattern.

5.2 Gas Transfer and Tidal Features

The residual maps (Figures 7 and **??**) clearly reveal gas structures that cannot be explained by simple rotating disk models. The most prominent feature is the gas bridge connecting NGC7752 to NGC7753, visible at velocities between 4900-5000 km/s. This structure represents tidally stripped material being transferred between the galaxies.

The amount of HI gas in the residuals is substantial, suggesting that a significant fraction of the neutral hydrogen in the system is not in regular rotation but is instead part of tidal streams and disturbed regions. This redistribution of gas is expected to have important consequences for star formation in the system, as the compressed gas in interaction regions can trigger star formation activity.

5.3 Challenges in Modeling Small Companions

Modeling 2MASX J23470758+2926531 proved particularly challenging due to its small size and the strong influence of NGC7753. The residuals show that even our best-fit model leaves significant unmodeled gas, suggesting that the kinematics of this galaxy are heavily perturbed by the interaction. This highlights the limitations of tilted-ring models for strongly disturbed systems, where the assumption of circular rotation breaks down.

5.4 Implications for Galaxy Evolution

The Arp86 system provides a snapshot of how galaxy interactions redistribute gas and affect the dynamics of all participants. The tidal features and gas flows observed here are likely driving enhanced star formation and will eventually lead to a merger of at least NGC7753 and NGC7752. The fate of 2MASX J23470758+2926531 is less certain because it may merge with the system or be ejected through gravitational interactions.

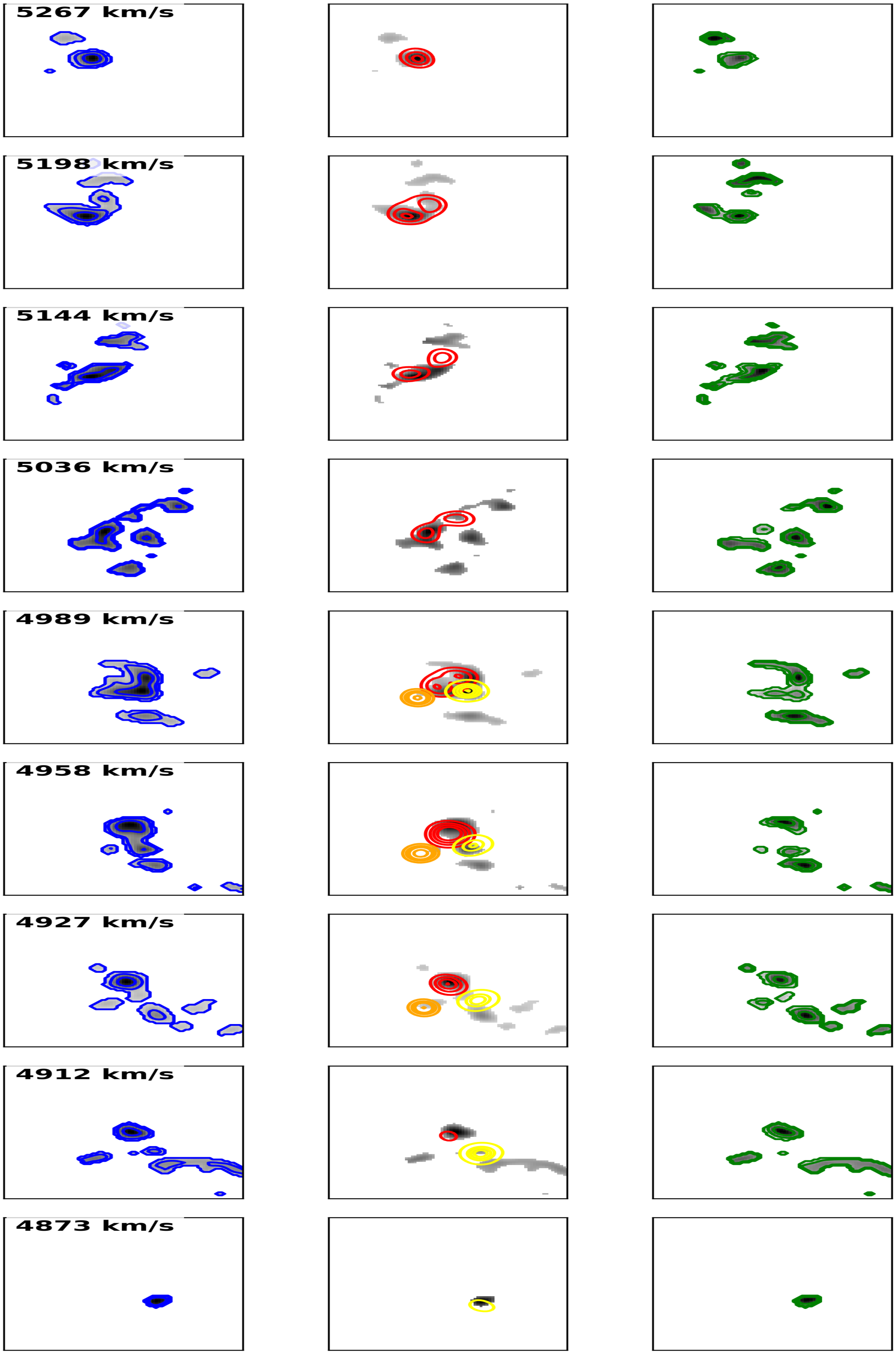


Figure 8: Comparison between observations of Arp86 (left) with the rotating BBarolo models (centre) and residuals (right)

6 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. We succeeded in modeling the three galaxies separately and get the kinematic parameters for each one. We expect that this procedure will also work for other interacting systems observed with APERTIF, allowing us to study the dynamics of gas in a variety of galactic environments. For future work, we could also analyze the mass distribution within each galaxy using the rotation curves obtained from the BBarolo models.

References

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