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, which 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 interacting 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 (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.

Neutral hydrogen (HI) gas is a fundamental component of spiral galaxies, playing a critical role in their formation, evolution, and ongoing astrophysical processes. The study of HI, primarily through its 21-cm emission line, provides invaluable insights into galactic structure, dynamics, and gas reservoirs (Sengupta et al., 2009). Observational studies have consistently demonstrated that HI in spiral galaxies is typically distributed in a disk-like structure (Beck, 2015). A significant portion of this gas resides in the outer regions of galaxies, with its density decreasing exponentially with increasing distance from the galactic center (Beck, 2015). More detailed mapping efforts reveal a complex network of HI filaments and clouds, exhibiting a wide range of densities and velocities (Schmidt et al., 2016). Beyond static distribution, the kinematics of HI within spiral galaxy disks are characterized by intricate dynamics. Studies, such as those on the massive spiral galaxy M83, show complex HI kinematics featuring multiple components and substantial non-circular motion (Pisano, 2014). These motions are understood to be influenced by internal galactic structures, including stellar bars and spiral arms, which drive gas flow and contribute to the observed kinematic complexity (Pisano, 2014). High-resolution HI observations are thus crucial for deciphering these detailed kinematic processes (Pisano, 2014).

A broad array of observational studies utilizing the 21-cm line have revealed the diverse properties of HI in spiral galaxies, encompassing a wide spectrum of gas masses and densities (Sengupta et al., 2009). This diversity underscores the varied evolutionary paths and internal conditions found across different spiral galaxy populations. Collectively, these investigations emphasize the critical role of HI in the formation and evolution of spiral galaxies. HI gas serves as the raw material for star formation, and its distribution and kinematics directly impact the star formation rate and efficiency within a galaxy. Furthermore, galactic encounters have been suggested to play a significant role in the evolution of early-type spiral galaxies, with HI dynamics being a key tracer of such interactions and their impact on galaxy properties (Zschaechner et al., 2012). Understanding the intricate interplay between HI distribution, kinematics, and its structural organization is paramount to unraveling the fundamental mechanisms governing spiral galaxy development. Continued research, particularly with advanced observational capabilities, remains essential to further elucidate the multifaceted role of neutral hydrogen in the cosmic evolution of these prominent galactic structures.

2 Observational Data

The data used for this research were 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 (Galactic coordinates, epoch 2000). It consists of three galaxies: the large barred spiral galaxy NGC 7753, its companion NGC 7752, and a third, smaller member, 2MASX J23470758+2926531 (Sengupta et al. (2009)). The data cube has three axes: two spatial dimensions (right ascension, RA, and declination, Dec) and one velocity (m/s) dimension. The data are in units of Jy/beam, representing the flux density per beam area. More information on the data header is available at 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.

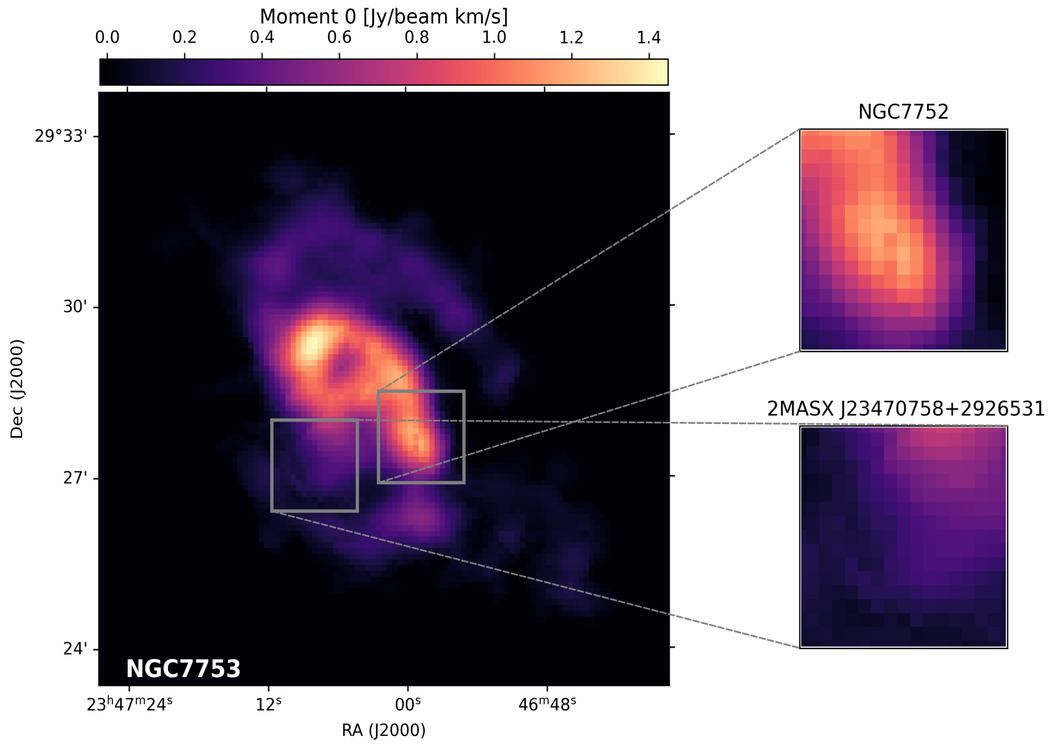


Figure 2: Integrated intensity (moment 0) map of the HI emission in Arp86, showing the distribution of neutral hydrogen gas across the system.

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 more detailed 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. The code is available in the GitHub repository. The first step in our data handling was to load the FITS file and inspect 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 three-dimensional FITS data cubes and creates a series of models as artificial 3D observations, which can be compared directly to the input data cube. It then finds a set of geometric and kinematic 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 lists 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

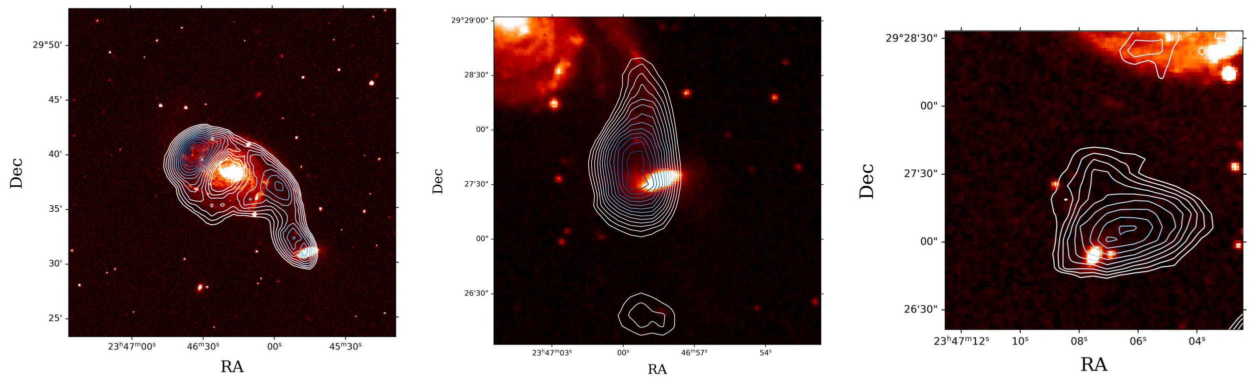
Table 3: Input parameters used in the 3DBarolo modeling of the third galaxy in Arp 86 (2MASX J23470758+2926531).

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 different models for this galaxy, and many of them were unsuccessful. We must be cautious when selecting the mask and the type of normalization. In this case, the number of rings used for fitting is smaller than in the first model of NGC 7753 because of the smaller size of the galaxy and the data cube. The number of rings depends on the radius of the galaxy, and the radius in pixels can be estimated using the moment 0 map and the optical image. This highlighted the importance of overlaying the intensity field with the optical image, which we used to compute the galaxy radius. The best modeling parameters for this galaxy are as follows. For modeling 2MASX J23470758+2926531, the essential parameter that allowed us to obtain a good fit with BBarolo was the number of rings. After estimating the radius of the galaxy, we specified to BBarolo how many rings to use to fit the data. In this case, the number of rings was 10. Although this is relatively small, BBarolo was able to produce a reasonable model with this choice. Another important parameter was the mask for the data; using the cube mask significantly improved the quality of the model.

4 Results

The first analysis we performed with Python focused on the integrated intensity, velocity field, and velocity dispersion of the whole system. The integrated intensity, or moment 0 map, represents the total HI intensity along the velocity axis. This map allows 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 plotted this map in red and blue colors to represent gas moving toward 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

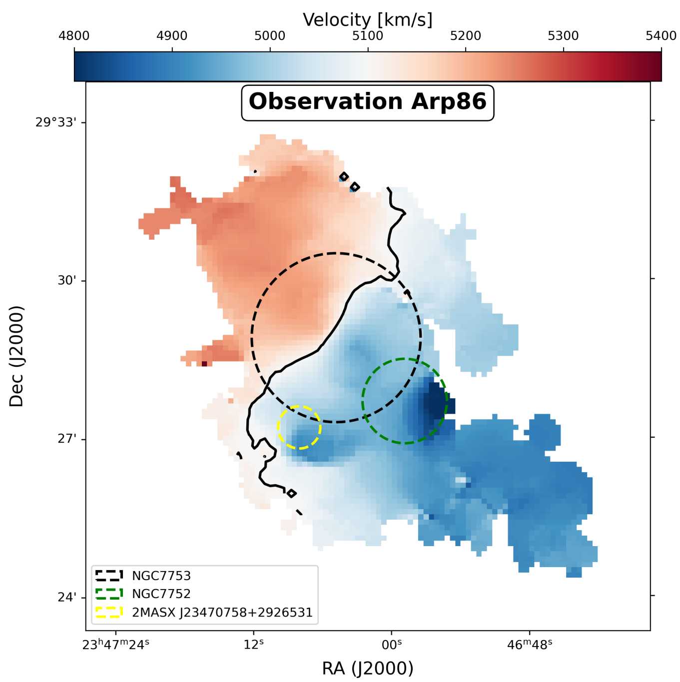
Figure 3: Optical image of Arp 86 overlaid with contours of neutral hydrogen (HI).

We also compared the HI features with an optical image. To do so, we downloaded the optical image of NGC 7753 from the DSS 2 Blue survey. Each moment map was reprojected using contour levels. The overlays were then plotted with consistent celestial coordinates (WCS) and axis labels (RA, Dec), as before.

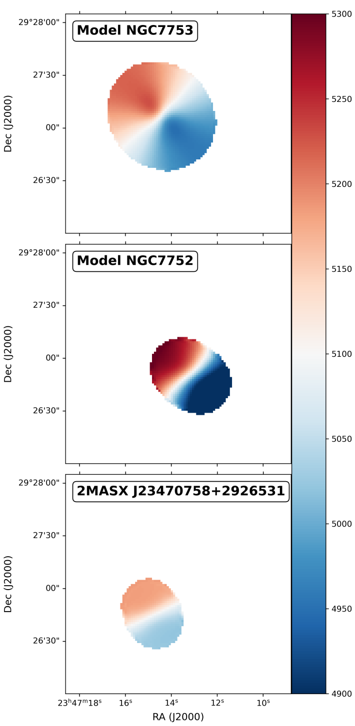
4.1 Analysis of BBarolo Model

In this section we present the results of the BBarolo modeling for the three galaxies in the Arp86 system. The velocity field of the system, along with the BBarolo velocity field for each galaxy, is shown in Figure 4. In Figure 4a, each galaxy is enclosed by a dotted circle with different colors for better visualization. Each circle was centered on the galaxy according to its pixel coordinates, and the radius was selected according to the size of each galaxy in the moment 0 map. The gas in the entire system is moving between approximately 4800 km/s and 5400 km/s. The large galaxy NGC 7753 is moving at higher velocities (approximately 5000 km/s to 5200 km/s). In contrast, the small companion NGC 7752 is moving at velocities of approximately 4900 km/s to 5300 km/s. The third galaxy, 2MASX J23470758+2926531, is moving at velocities different from the other two (approximately 5000 km/s to 5100 km/s). This behavior is expected since the large galaxy has higher mass and therefore a deeper gravitational potential, but NGC 7752 shows interesting features in its velocity field due to its interaction with NGC 7753.

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. For NGC7753, the residuals are relatively small and mostly located in the outer parts of the disk, which means that the model reproduces the main rotating pattern of the galaxy quite well. In contrast, NGC7752 and 2MASX J23470758+2926531 show stronger and more asymmetric residuals, especially in the regions between the galaxies, where we expect gas to be disturbed by the interaction. This comparison confirms that while the tilted–ring models capture the bulk rotation of each disk, they do not fully describe the disturbed gas associated with tidal features and gas flows within the system.

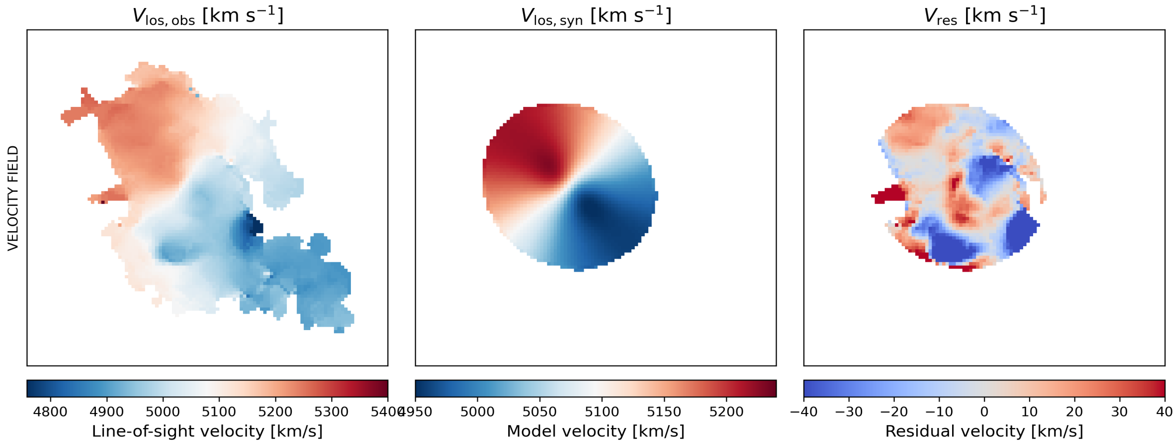


(a) Velocity field observation

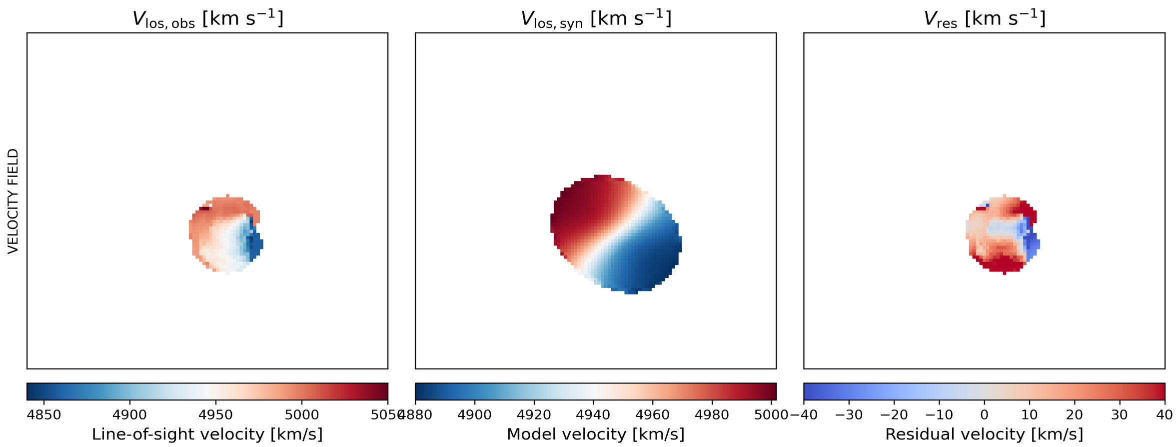


(b) Velocity field models

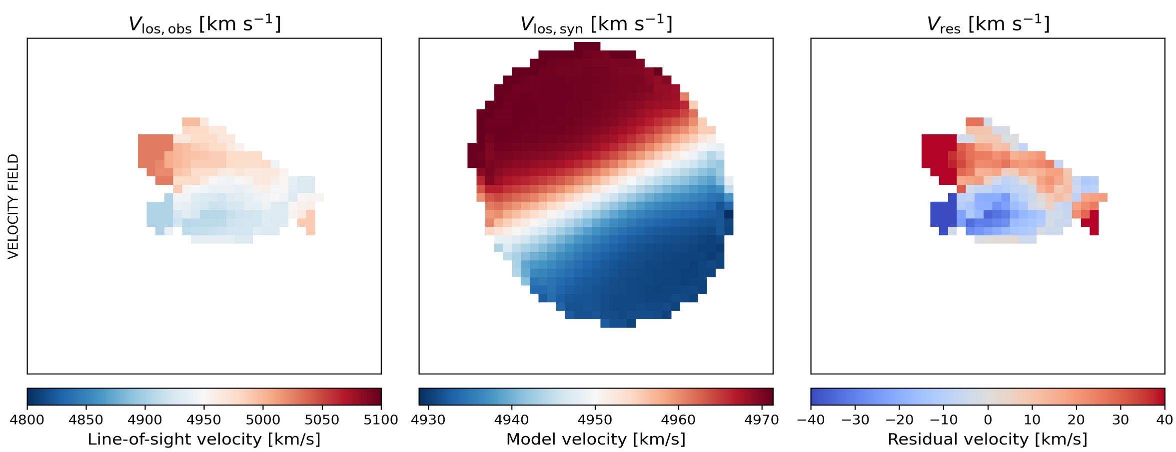
Figure 4: (a) Velocity field of the Arp86 system from observations. (b) Velocity field models for each galaxy in the system: NGC7753 (red), NGC7752 (green), and 2MASX J23470758+2926531 (blue). Each galaxy is enclosed by a dotted circle for clarity.



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



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

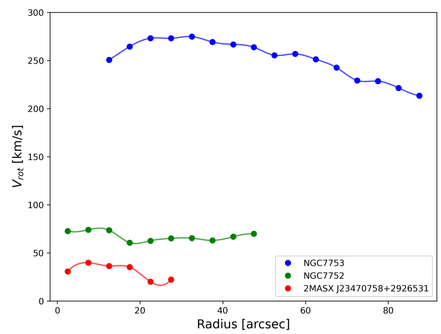


(c) 2MASX J23470758+2926531: Comparison between observational data, Barolo model, and residuals.

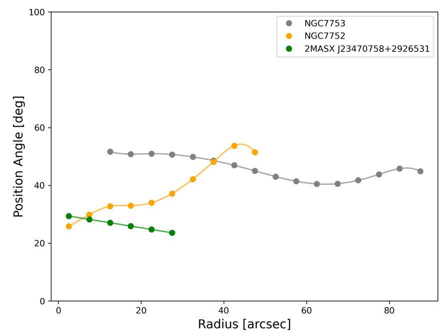
Figure 5: Comparison between the observational data, BBarolo models, and residuals for the three galaxies in Arp86.

4.2 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 NGC 7753, NGC 7752, 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.

4.3 Residuals

After modeling the three galaxies in the Arp86 system, we proceeded to compute the amount of gas that is not fitted by the models. To do so, we used the residuals obtained from each model. The residuals are calculated 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 flows between the galaxies or tidal interactions.

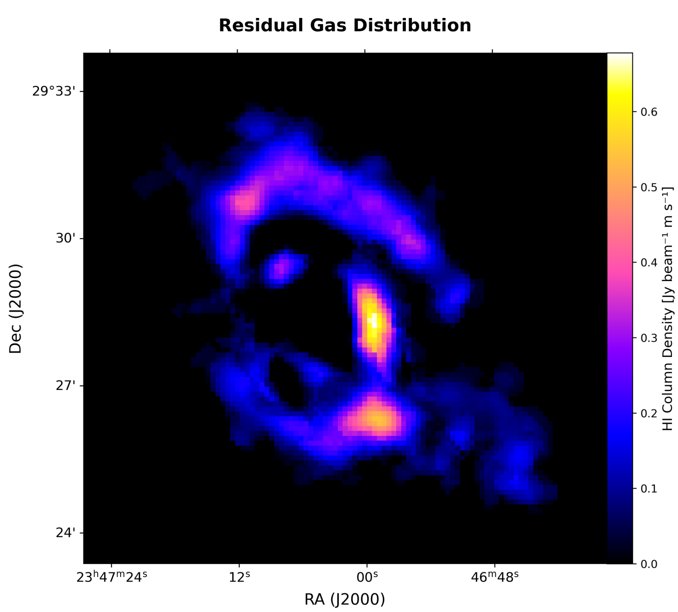


Figure 7

4.4 Kinematic Modelling of the System

Figure 8 shows the BBarolo model of each galaxy together with the residuals. The model of NGC 7753 has red contour lines, NGC 7752 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 gas that is not fitted by the models; this gas is due to the interactions between the galaxies. Gas flows from NGC 7752 to NGC 7753 are clearly visible in the residuals. Each panel is plotted at a different velocity channel, so we can clearly see at which velocities the gas belonging to each galaxy is located. The large galaxy (NGC 7753) is moving at higher velocities, while the smaller galaxies are moving at lower velocities. We expect this behavior since the large galaxy has higher mass and therefore higher gravitational potential. We can see that at approximately 4910 km/s the model of 2MASX J23470758+2926531 disappears, but there is still gas at that location, which suggests that the model is not yet perfect.

5 Discussion

5.1 Reliability of the models

The HI rotation curves of the three galaxies exhibit a typical behavior for spiral galaxies, 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 NGC 7753, 120 km/s for NGC 7752, and 80 km/s for 2MASX J23470758+2926531, reflecting their relative masses and sizes. Figure 5 allows a direct comparison between the observed velocity fields and the BBarolo models. For the three models, we see overall residual velocities between -50 km/s and $+50$ km/s, indicating that the models capture the bulk rotation of the disks reasonably well. However, for NGC 7752 and 2MASX J23470758+2926531, there are larger and more complex residuals, suggesting that these galaxies are more strongly affected by the interaction, or that the tilted-ring model is less adequate for their disturbed kinematics. From the residual integrated intensity map of the entire system (Figure 7), we see that there is a significant amount of HI gas that is not fitted by the models. To the northeast of NGC 7753, there is a prominent spiral arm structure. To the north of NGC 7752, there is a gas bridge connecting it to NGC 7753. These features are the result of tidal interactions between the galaxies, which redistribute gas and create complex flows that deviate from simple rotation, a well-known behavior for this kind of galaxy group, such as the M81 group (Yun et al. (1994)). To the south of NGC 7752, there is also a tidal tail structure whose origin is unclear. The position angle variations with radius (Figure 6b) show significant deviations from constant values, particularly for NGC 7752 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 Challenges in Modeling Small Companions

Modeling 2MASX J23470758+2926531 proved particularly challenging due to its small size and the strong influence of NGC 7753. 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.

5.3 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 may eventually lead to a merger of at least NGC 7753 and NGC 7752. The fate of 2MASX J23470758+2926531 is less certain because it may merge with the system or be ejected through gravitational interactions.

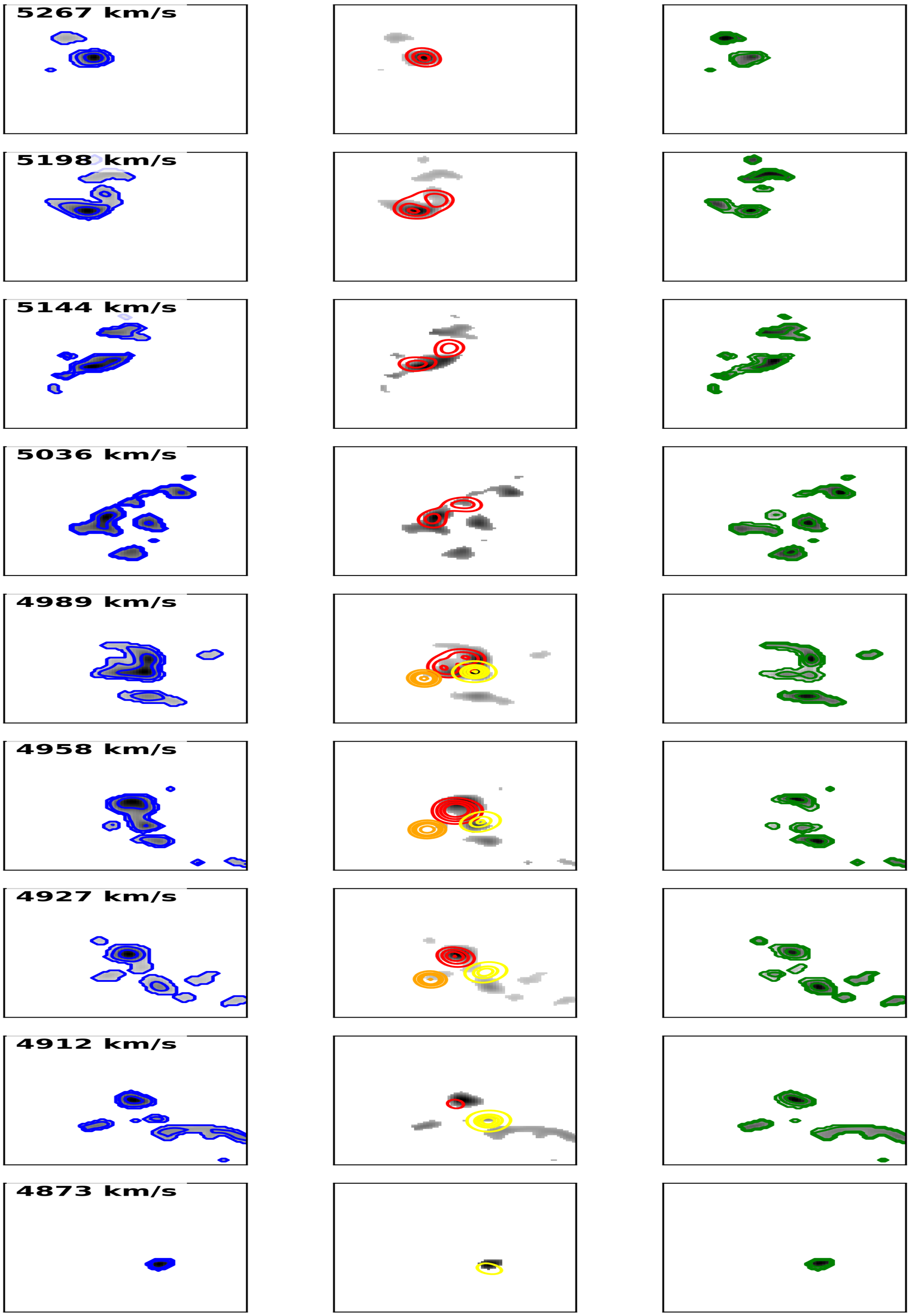


Figure 8: Comparison between observations of Arp86 (left) with the rotating BBarolo models (centre) and residuals (right)

6 Conclusion

In this work, we have presented a kinematic model of the Arp86 system 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 in obtaining 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.

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