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Merging of spiral galaxies: observations and modeling

A. Khoperskov[1], S. Khrapov[1], D. Sirotin[1], and A. Zasov[2,3]

[1] Volgograd State University, 100 Prospect Universitetsky, Volgograd, 400062 Russia
[2] Sternberg Astronomical Institute, Moscow M.V. Lomonosov State University,
13 Universitetskij pr., Moscow, 119234 Russia
[3] Faculty of Physics, Moscow M.V. Lomonosov State University, 1 Leninskie gory, Moscow,
119991 Russia

Abstract. We present a study of the dynamics of multi-component models of spiral galaxies at different stages of grand mergers. The numerical models include a self-consistent account of the dynamics of collisionless stellar subsystems and N-body dark matter, as well as gaseous components. The calculation of gas heating and cooling processes allows us to consider a wide temperature range from 80 to 100 thousand degrees. The use of the method of Smoothed-particle hydrodynamics to solve the hydrodynamic equations makes it possible to follow the evolution of the gas of each galaxy, calculating the content of gaseous components of each object in the process of complex exchange of matter. The gravitational interaction is determined in a direct way by summing the contributions according to Newton's law, which minimizes the modeling error. This requires significant computational resources using graphics accelerators on a hybrid computing platform CPU + multi-GPUs. The study aims to reconcile theoretical models with the morphology and kinematics of a number of observed systems. In particular, Taffy-type objects are considered, where two galaxies are connected by a gas bridge with a characteristic small-scale gas structure after the disks have passed through each other in an approximately flat orientation. Examples of such systems are the observed galaxy pairs UGC 12914/UGC 12915, NGC 4490/NGC 4485, UGC813/UGC816 etc.

Keywords: galaxies: interactions, evolution, structure

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1 Introduction

Galactic interactions are the most important factor in the evolution of a significant fraction of these stellar systems. The most large-scale events are associated with major mergers, leading to the formation of complex tidal structures, a significant restructuring of star formation history, determining the morphology and kinematics in the process of merging of galaxies (Condon et al. 1993; Lisenfeld et al. 2019; He et al. 2024).

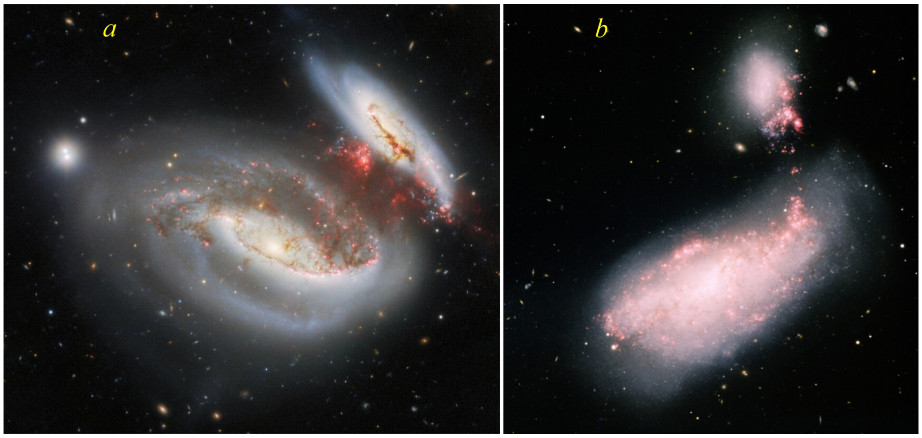

Fig. 1. Images of Taffy galaxies: *a* — UGC 12914 (bottom) and UGC 12915 (top); *b* — NGC4490 and NGC4485 (Gemini North, https://noirlab.edu).

A very curious and rare class of interacting objects are the systems of recently collided disky galaxies, the study of which began with the pair UGC 12914/12915, called Taffy (Condon et al. 1993). A near head-on collision occurred about 25 million years ago, and a gas bridge with a peculiar morphology and physical state of matter is clearly visible between the disks of the galaxies (Fig. 1).

The goal of this paper is to construct numerical dynamical models of a nearly face-on collision of two S-galaxies that reproduce the main properties of the observed of Taffy-like objects. The model of each galaxy includes stellar and gas disks immersed in a living dark halo. We study the influence of various parameters of the galactic pair on the properties of the gas bridge observed in the in the Taffy and Taffy-like systems.

2 Features of Taffy pairs and their modeling

The pair UGC 12914/12915 is a classic example of Taffy galaxies, which was highlighted in the work of Condon et al. (1993). The presence of thin filamentary gas structures between two S-galaxies is a distinctive feature of Taffy. This observed feature is formed as a result of the recent passage of the disks through each other.

Some characteristics of UGC 12914/12915 are as follows (Condon et al. 1993; Lisenfeld et al. 2019; He et al. 2024; Joshi et al. 2019). 1) An almost head-on collision of two counter-rotating disks occurred several tens of millions of years ago. 2) There is a massive multiphase gas bridge containing filamentary structures. 3) The gas bridge containes warm molecular hydrogen. 4) Star formation in the bridge is low, if any, and apparently suppressed by the strong gas turbulence. 5) The soft X-ray emission from the bridge is associated with hot gas with a mass in the range of $(0.8–1.3) \times 10^8 M_\odot$, which is about 1% of the total mass of the gas between the disks (Appleton et al. 2015).

The pair NGC 4490 and NGC 4485 is also Taffy-type (Fig. 1), although the impact geometry was apparently different from the UGC 12914/12915 system. Note that warm molecular hydrogen has been detected in gas outflows in M82. Such superwinds are a fairly common phenomenon, and their structure is also filamentary.

3 Numerical simulation of Taffy galaxies

We present preliminary results from simulations of two colliding galaxies, each containing a stellar disk, a gas disk, and a dark halo. The basic model consists of identical galaxies with star masses $M_d = 3.72 \times 10^{10} M_\odot$, gas $M_g = 3.72 \times 10^9 M_\odot$, dark matter $M_h = 6.02 \times 10^{10} M_\odot$ (within the optical radius $R_{\rm opt} = 9$ kpk). The total mass of the simulated dark halo is $24.92 \times 10^{10} M_\odot$ in each galaxy.

Two galaxies with stellar disks of masses $M_d^{(1)}$ and $M_d^{(2)}$ and dark halos of masses $M_h^{(1)}$ and $M_h^{(2)}$ are simulated by collisionless N-body particles. The gas dynamics are computed by the smoothed-particle hydrodynamics (SPH) method. The gravitational interaction is calculated by summing of the contributions of all particles (N-body + SPH-particles) (Khoperskov et al. 2024, 2021; Titov & Khoperskov 2022).

Figure 2 shows the distribution of gas density along the line of sight during a head-on collision of two identical galaxies. The time $t = 183$ Myr corresponds to the first contact of the gas disks. The following frames show the formation of a gas bridge between the galaxies. Filamentary structures are a characteristic feature of the dynamics of the gas ejected by the impact. The bridge region contains no stars. The flat-type impact considered distorts the stellar disk much less than the gas disk, which undergoes the dramatic changes.

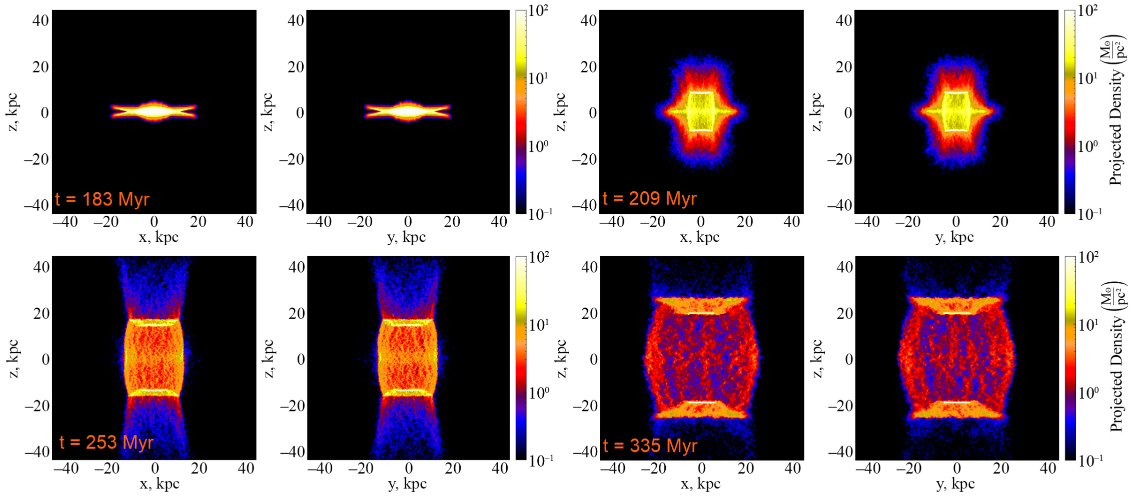

Fig. 2. An example of a head-on collision simulation of a Taffy-type pair with retrograde rotation of the disks.

The following regions of the Taffy system can be conditionally distinguished (see Fig. 2): I — gas inside stellar disks; II — gas bridge between galactic disks, defined by the conditions $z_1^{(\rm disk)} < z < z_2^{(\rm disk)}$, $r < R_{\rm gas}^{(\rm disk)}$; III — outer zone relative to the bridge between the galaxies, $z_1^{(\rm disk)} < z < z_2^{(\rm disk)}$, $r > R_{\rm gas}^{(\rm disk)}$, IV and V — remaining zones outside the galactic disks, $z > z_1^{(\rm disk)}$ (IV), $z < z_2^{(\rm disk)}$ (V). Figure 3 shows the evolution of the gas abundance with time for these four regions.

Figure 4 shows the distribution of gas between the disks as function of gas temperature for a symmetrical head-on impact. Hot gas at a temperature of 3000–10000 K is fairly uniformly distributed. There are only remnants of increased concentration near the plane of symmetry ($z = 0$), which is associated with the position of the initial impact. Relatively cool gas (100–500 K) forms inhomogeneous filamentary structures.

The cold gas forms a shell structure in contrast to the hotter component, which occupies the entire volume of the bridge. This feature is due to the complete symmetry of the system when two identical galaxies collide. Simulating the impact of dissimilar galaxies, or the lack of geometric symmetry of the initial interaction, critically alters the properties of the gas bridge.

The overall result is that the gas bridge can contain up to 90% of the total gas mass immediately after the collision. This mass decreases to 30% as the disks move away from each other. The bridge loses gas due to gas deposition on the disks of the galaxies and gas expansion in the bridge region. We calculate the gas fractions in each

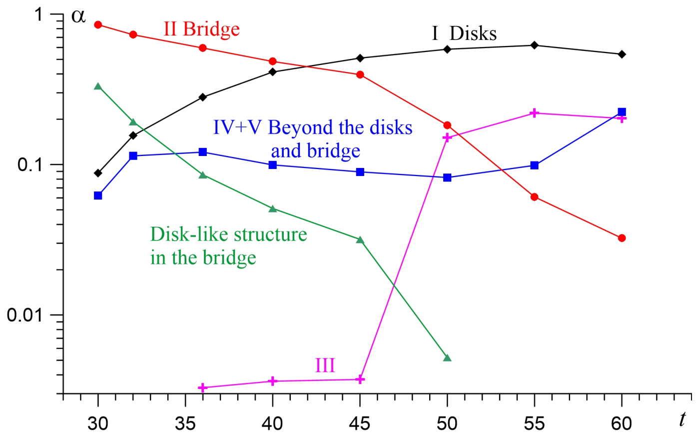

Fig. 3. Dependence of the gas mass in the different regions of the interacting system during the evolution process, $t = 1 \to 63.2\,\mathrm{Myr}$.

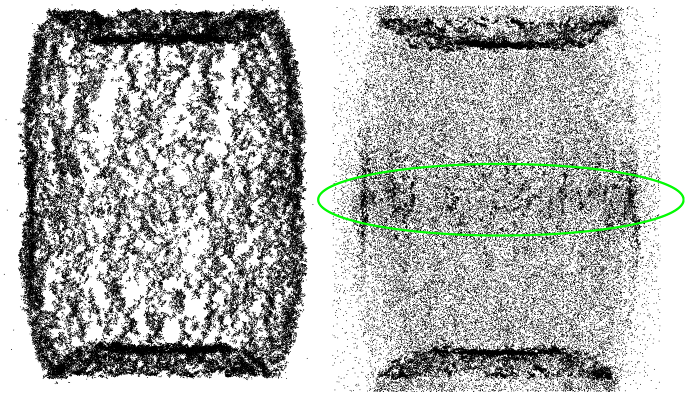

Fig. 4. Structure of warm gas (left) and neutral hydrogen (right) between galaxies 70 million years after the initial impact. The disk-like structure in the bridge area is highlighted by the green line.

region of each galaxy separately. For example, $\alpha_1^{(\mathrm{I})}$ is the fraction of the gas mass in region I from the first galaxy. If the initial galaxies are not identical or the collision geometry is not symmetric, then $\alpha_1^{(\mathrm{II,III})} \neq 1/2$. Computational experiments show a rather strong dependence of the α parameter on the collision conditions. We also calculate the enrichment of the first galaxy in the gas of the second one and vice versa. These properties $\alpha_{12}^{(\mathrm{I})}$ and $\alpha_{21}^{(\mathrm{I})}$ are quite sensitive to the initial collision conditions. The green line in Fig. 3 shows the presence of a massive disk-like structure in the bridge region (more than 30% of the total gas) immediately after the collision in the $z = 0$ plane for identical galaxies (see Fig. 4). However, this gas quickly dissipates.

Figure 4 (right) shows the remaining remnants of this gas 70 million years after the initial impact.

4 Summary

The results allow us to account for the presence and a structure of inhomogeneous multi-component media observed in Taffy-type galaxies. We have performed more than 30 computational experiments to study the structures formed when disk galaxies collide almost face-on. The main focus of the study is to determine the properties of the gas in the bridge region between the disks of the galaxies. Our results show that the spatial structure of the gas and its thermodynamic properties are very sensitive to the impact geometry and parameters of the parent galaxies. Our numerical models allow us to distinguish gas components that form the spatially distinct subsystems with different temperatures in the range of $50 \div 2 \cdot 10^5$ K.

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