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Peculiar pairs of ARP galaxies in numerical simulations

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Abstract. Using simple late-type galaxy models in N-body simulations, we search for the initial conditions that could replicate the morphological structure of the peculiar pair ARP 273. The best scenario found is that of recent a collision of the smaller galaxy through the disk of the major one, about 150 Ma before. We then analysed the Fourier decomposition of the perturbed disks after the encounter, as to investigate the evolution of spiral and bar structure in both galaxies.

Resumo. Usando modelos simples de galáxias de tipo tardio em simulações de N-corpos, nós procuramos por condições iniciais capazes de replicar a estrutura morfológica do par peculiar ARP 273. O melhor cenário encontrado caracteriza uma colisão recente da menor galáxia com o disco da maior, cerca de 150 Ma antes. Analisamos, então, a decomposição de Fourier dos discos perturbados após o encontro, a fim de investigar a evolução de estruturas espirais e barras em ambas galáxias.

Keywords. Galaxies: interactions – Galaxies: peculiar – Methods: numerical

1. Introduction

Amongst the events that shape the evolutionary history of galaxies, interactions and mergers are processes that can violently alter the structure and morphology of these systems. The Catalogue of Peculiar Galaxies by Arp (1966) gathers some remarkable examples of interactions, as well as other type of phenomena.

Encounters like these allow us to study perturbative structures such as bars, spiral arms, tidal tails, bridges, etc. (Struck 1999). Since early times, dynamical N-body modelling was shown to be a great tool on analysing the formation of these peculiar structures in real galaxies (Toomre & Toomre 1972).

In comparision, today state-of-the-art simulations of galaxy evolution must consider many effects such as supernova and AGN feedback mechanisms that regulate star formation at galactic scales, and also the effect of environment through cosmological simulations (Naab & Ostriker 2017).

This work is a case-study of a specific galaxy pair, ARP 273, with its main galaxy UCG 1810 at redshift 0.025. We attempt to find the right initial conditions where an encounter of two simple disk-type galaxies could generate the peculiar morphology that is observed in high resolution optical imaging.

2. Methods

We generated initial conditions following the code MaGalie (Boily, Kroupa & Penarrubia-Garrido 2001), available in the NEMO Stellar Dynamics Toolbox package (Teuben 1995). The late-type galaxy models are near-equilibrium, idealized systems with an exponential disk density profile, a spherical bulge from a Hernquist profile (i.e. Hernquist 1990), and a NFW dark matter halo (i.e. Navarro, Frenk & White 1997).

We focus, initially, in a simplified non-collisional model, without the inclusion of gas. This decision is motivated initially by simplicity, due to the intricate endeavor of finding the initial conditions of a specific galaxy pair. However, as will be seen, it is a likely scenario that ARP 273 is at the initial stages after their first passage. For this reason, it is a reasonable approximation that the mass distribution, at least for the observed morphology, is mainly shaped by the interaction of non-collisional matter rather than the gas dynamics.

To replicate the observed structure of ARP 273 interaction, we needed to find an optimal set of parameters. Amongst them, are: structural parameters such as the mass of the halo M_H, disk M_D, and bulge M_B of both galaxies, as well as their dimensions with scale lengths a_D, a_B, a_H and b_H; the relative orientations (i_1, ω_1) and (i_2, ω_2) of both disks; the eccentricity e and semi-latus rectum p of the initial Keplerian orbit, that are related to the initial orbit's energy and angular momentum; and finally the viewing angle (θ_x, θ_y) and time t, corresponding to the actual observation.

These initial conditions were then run with the N-body integrator GyrfalcON that implements the efficient Fast Multipole Method described by Dehnen (2002).

The disks generated were stable, with a Toomre Q parameter of 1.5, and we also took care to mantain energy and angular momentum conservation to within 0.1% throughout the integration.

We used two observational parameters to constrain the units of the simulation: the visual diameter of UGC 1810, and the relative line-of-sight velocity $v_{\rm LOS}$ of both galaxies, obtained through the difference between their individual redshifts Δz, and the average value $\bar{z}$, using Eq. (1). With values of z from de Vaucouleurs et al. (1991), the relative line of sight velocity is $190\,{\rm km\,s^{-1}}$, and UGC 1813 is approaching the observer relative to UGC 1810.

$$v_{\rm LOS} = c\frac{\Delta z}{1+\bar{z}}\,. \tag{1}$$

3. Results

The best-fit model that describes the encounter between UGC 1810 and UGC 1813 can be seen in Fig. 1a. The scenario was such that the smaller galaxy had a non-central collision through the disk of the larger one at approximately 150 Ma before its current configuration.

Their initial orbit was set as parabolic, with a value for p of 34 kpc, that would correspond to a closest approach of 17 kpc in this case. The actual pericentric distance in the simulation is 23 kpc, since other effects such as extended-body interactions

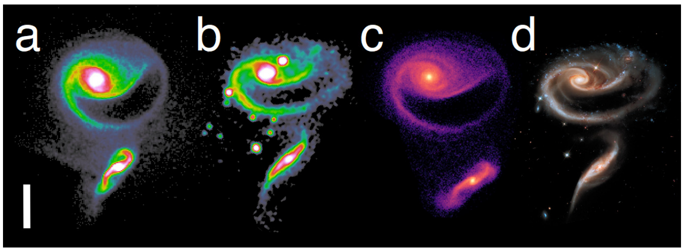

Figure 1. Comparison of different images, simulated and observed, of Arp 273. The white bar has length of 20 kpc. From left to right: a. Projection of the best scenario for the encounter; b. DSS2 IR image, that better represent the mass distribution of the system; c. Same simulation with a shift of 20 Ma in time and 8° in viewing angles, showing perceived differences from variations in projection and color scheme; d. Composite image from the HST, credits to NASA, ESA and the Hubble Heritage Team (STScI/AURA).

and dynamical friction take place (Binney & Tremaine 2008, pp.643-651).

Both disks were perpendicular to the orbit's plane (such that $i = -90°$), and had arguments of periapsis $\omega_1 = -40°$ for the bigger galaxy and $\omega_2 = 15°$ for the smaller one.

In this scenario, the system has a total mass of 1.96×10^{12} $M_\odot$, a mass ratio of 5:1 for both galaxies, with the fraction of stellar mass to total mass being $f_{L,1} = 0.05$ for UGC 1810, and $f_{L,2} = 0.1$ for its companion.

We then analysed how the disk of both galaxies is perturbed and evolves after their first passage. For that, we divide radially the face-on disk of the galaxies in discrete concentric rings, and Fourier-decompose the azimuthal density profile at each radius. This method is described in Binney & Tremaine (2008, p.469) and is also similar to Aguerri et al. (1998).

This decomposition can be seen in Fig. 2. We can see that the collision is responsible for asymmetries in the disk of UGC 1810, as seen in the $m = 1$ mode with it's bigger spiral arm, that also is characterized as an edge-on warp in the disk; and $m = 3$ with bifurcations that can be seen in the HST image, Fig. 1d. It is possible to note that the $m = 2$ pattern is maintained at a inner radius, and even amplified. A possible explanation is the swing amplification mechanism (Toomre 1981) due to the interaction of self-gravity, differential shear and epicyclic rotation frequencies in the disk.

Unlike its larger companion, UGC 1813 gets heavily disturbed tidally in such a way that mostly symmetric modes $m = 2$ are induced in long streams that extend outward from the galaxy. The disturbance is such that the disk becomes unstable and develops a bar, that rotates with a higher pattern speed than its spiral arms.

We also applied the 2D Fourier decomposition from Considère & Athanassoula (1982), that results in double spiral arm strength of $A_2 = 0.22$ for UGC 1810. With this approach, it is also possible to determine a pitch angle of $\phi = 32°$ that decreases with time, in agreement with the view that interaction induced spiral arms are probably temporary (Binney & Tremaine 2008, pp. 473-474, 480), winding-down after the encounter.

4. Discussion and Conclusion

In this work, we have developed a model for the dynamical history of the galaxy pair Arp 273 that successfully replicates a significant portion of the observed morphological phenomena, seen in 1b. This includes the prominent spiral arm of UGC 1810, its

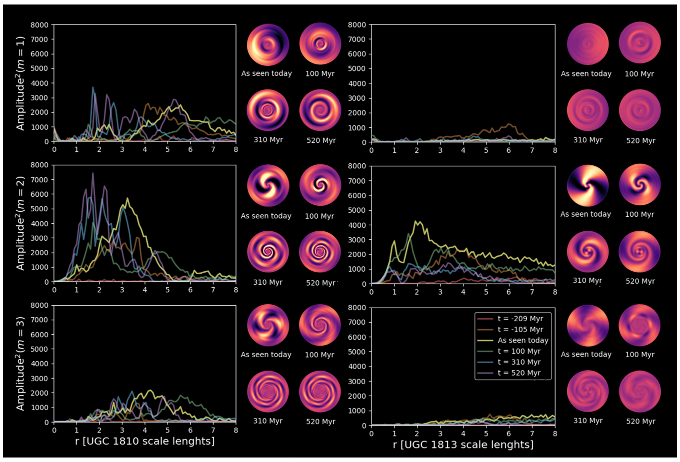

Figure 2. Temporal Evolution of the three first Fourier components of the stellar disk of both galaxies. It is possible to note the formation of a bar in UGC 1813, as well as the winding down of UGC 1810 spiral arms.

smaller bifurcated opposing arm, and the elongated appearance of UGC 1813.

However, certain discrepancies in shape and diffuse particle distribution are noticeable. Care must be taken, however, when expecting exact models for the structure of a real system. Firstly, there could be differences from numerical resolution problems and finding the optimal parameters, that by itself is a non-linear optimization problem that can have degeneracies (Barnes 2016). But also could depend on how detailed are the models chosen, since the progenitor galaxies may not follow simple featureless disk morphology.

In the future we aim to refine our description, simulating additional components such as gas with feedback models, in order to study in more detail other phenomena related to galaxy evolution and mergers (Hopkins et al. 2013). Future perspectives are also on more efficient and automated ways to explore parameter space (e.g. West, Ogden, & Wallin 2023), and finally extending the modelling and analysis to other Arp galaxy pairs.

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