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THE IMPORTANCE OF INTERACTION STRENGTH FOR NON-MERGER GALAXY ENCOUNTERS

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Abstract. Galaxy flybys, a class of non-merger interactions, outnumber mergers at lower redshifts (e.g. $z \leq 2$), particularly in higher-density environments. Some of the previous research adopted merger-based classification based on the mass ratio of interacting galaxies, differentiating between equal-mass and lower-mass flybys (i.e. major versus minor). However, cosmological simulations showed that major flybys are extremely rare and almost exclusively distant, while minor ones are much more frequent, with the secondary galaxy penetrating deep into the primary. We demonstrated that this leads to comparable strengths of interaction between the two sub-classes and essentially the same effects. Focusing on morphological consequences, we will showcase a few examples (formation of spirals, bars, and some complex structures). Thus, flybys should be classified primarily based on the interaction strength and explored further as they contribute to the structural diversity of galaxies observed in the local Universe.

1. INTRODUCTION

Galaxy encounters can be classified based on many different characteristics. The primary and the most fundamental classification is based on the outcome: do the interacting galaxies eventually merge into one, or do they continue their post-interaction evolution as separate and distinct objects? In other words, galaxy encounters are primarily classified into mergers and non-mergers. Hierarchical structure formation, the idea that the present-day galaxies and larger structures (e.g. galaxy groups and clusters) formed due to successive mergers throughout cosmic history, is an integral part of the Standard cosmological model (ΛCDM). Thus, it should not be surprising that mergers are intensely studied, and their classifications are well-defined and widely accepted, while non-mergers have received far less attention. Consequentially, merger classifications have made their way into the research of non-merger encounters, particularly the most common one based on the mass ratio: major (if the interacting galaxies have comparable masses) or minor (if one of the galaxies is significantly more massive than the other). This work aims to demonstrate that such a practice is unfounded, as non-merger encounters are far more subtle, and their consequences depend on various other parameters. For this purpose, galaxy flybys, a class of non-merger interactions, will be used as an example. However, the major takeaway points and conclusions should apply to any non-merger encounter.

Galaxy flyby is an interaction where two independent halos inter-penetrate but detach at a later time. Thus, it represents a specific class of non-merger encounters, very close interactions that can potentially influence the evolution of individual interacting galaxies in a significant way. Statistical analysis of cosmological simulations

(Sinha & Holley-Bockelmann 2012, Sinha & Holley-Bockelmann 2015, An et al. 2019) has shown that these interactions are as frequent as mergers and even surpass them by order of magnitude at lower redshifts ($z \leq 2$) for sufficiently high-mass primary galaxies ($M \geq 10^{11} M_{\odot} h^{-1}$). Moreover, these studies have found that for high-mass primary galaxies (e.g. present-day Milky Way-like galaxies), galaxy flybys happen with the typical mass ratio $q \leq 0.1$, when the secondary galaxy penetrates deeper into the primary, typically at lower pericentric distances than $R_{\rm half}$ (half-mass radius of the primary) with high relative velocities ($v_{\rm rel} > 420$ km s^{-1}). By contrast, higher-mass ratio galaxy flybys for massive primaries are extremely rare and almost exclusively distant. If we adopt a merger-based classification, these results imply that *minor* flybys significantly outnumber *major* ones.

Given that the frequency of galaxy flybys, particularly at lower redshifts, is high enough, it was reasonable to assume that these interactions have the potential to significantly impact the evolution of individual galaxies in the Local Universe. Thus, several authors explored their effects, primarily of a morphological nature, in controlled, isolated simulations with better temporal resolution (e.g. Kim et al. 2014, Lang et al. 2014, Pettitt & Wadsley 2018, Łokas 2018, Kumar et al. 2021). However, the majority of these studies either focused on equal-mass flybys or adopted merger-based classification. This has led Lang et al. (2014) to conclude that only *major* flybys can induce bar formation in the primary galaxy. The conclusion is at odds with what we know about tidally induced bars (in particular, that they can form due to weaker external perturbations).

In our previous research (Mitrašinović 2022, Mitrašinović & Micic 2023), which we will use as an example, we set our aims to explore galaxy flybys, taking into account their typical characteristics obtained from cosmological simulations. When these characteristics are taken into account, *minor* and *major* flybys should have comparable strengths of interaction[1] and, consequentially, lead to similar effects. Thus, it essentially makes these two classes of flybys indistinguishable, at least based on this particular classification scheme.

This work is organised as follows. In Section 2, we will introduce and discuss the notion of interaction strength. We will present examples from our previous work in Section 3 and discuss them in the relevant context. Finally, we will give concluding remarks in Section 4.

2. INTERACTION STRENGTH

The interaction strength, as a notion, has emerged from the idea that the gravitational interaction between two objects can be quantified with a single number, depending on various relevant parameters. The complete list of relevant parameters includes masses of individual interacting objects, their radial extents (if applicable), the relative velocity of the secondary object viewed from the reference system of the primary (which implicitly determines interaction timescale, i.e. duration) and the minimum distance between the objects during the interaction, which is called the impact parameter. Sometimes, in literature, terms *impact parameter* and *pericenter* are used interchangeably - however, there are subtle differences. The term *pericenter* is related to the orbit of a secondary object (and solely represents the orbital posi-

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[1] The focus of this contribution.

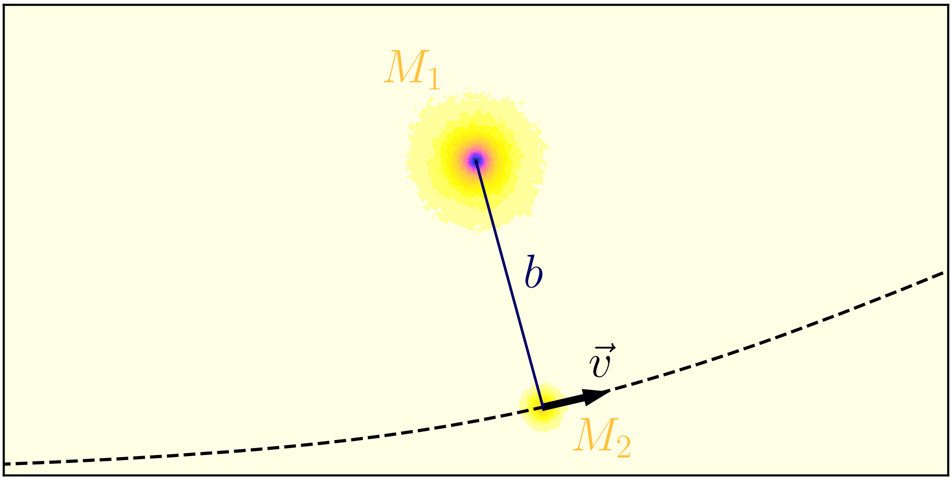

Figure 1: Simplistic two-dimensional view of a non-merger (planar) interaction between two galaxies - a primary galaxy with mass M_1, and a secondary with M_2. The primary galaxy is centred in the reference system, while the secondary is moving in orbit (dashed black line) with the relative velocity $\vec{v}$. The illustration shows the moment when the minimum distance between the galaxies (during the interaction) is reached (blue solid line), which is called the impact parameter (denoted by b).

tion when the minimum distance is reached). The term *impact parameter* defines the actual minimum distance. Figure 1 shows a simplistic two-dimensional view of the non-merger encounter, with the most relevant parameters marked and defined within the label (with the exclusion of the radial extents of interacting objects). Despite being a simplistic representation, it will help define the interaction strength before discussing major caveats and realistically considering non-merger encounters.

There are several ways in which the interaction strength can be quantified - Oh et al. (2015), for example, discuss a few, most commonly used ones. The simplest one takes into consideration only the mass ratio of interacting galaxies, the radial extent of the primary galaxy and the impact parameter. It is traditionally denoted with P and defined as:

$$P = \frac{M_2}{M_1}\left(\frac{R_1}{b}\right)^3 \tag{1}$$

where R_1 represents the radial extent of the primary galaxy, and the other parameters were previously defined. This definition is used when the radial extent of the secondary R_2 is either much smaller than the impact parameter b (and could, thus, be neglected) or when the focus of the research project is on the primary galaxy and the secondary is much more compact in comparison. On the contrary, if the radial extent of the secondary needs to be accounted for, the Equation 1 becomes:

$$P = \frac{M_2}{M_1}\left(\frac{R_1}{R_2 + b}\right)^3. \tag{2}$$

Both of these two definitions suffer from the same problem - they do not account for the duration of the encounter, either explicitly or implicitly (e.g. through the relative velocity). In that sense, a more complete interaction strength parameter, which takes into account the interaction duration, is suggested by Elmegreen et al. (1991) and traditionally denoted with S. It is calculated as:

$$S = \frac{M_2}{M_{\mathrm{gal}}\big(R < R_{\mathrm{gal}}\big)}\left(\frac{R_{\mathrm{gal}}}{b}\right)^3 \frac{\Delta T}{T} \tag{3}$$

where M_2 and b were previously defined, while R_{gal} represents an effective radius of the primary galaxy (i.e. the extent of its visible component), M_{gal} is the total dynamical mass of the primary enclosed within R_{gal}, T is also related to the primary and calculated as $T = (R^3_{\mathrm{gal}}/GM_{\mathrm{gal}})^{1/2}$ and ΔT represents a measure of interaction duration and depends on relative velocity $\vec{v}$. More specifically, ΔT represents the time required for the secondary galaxy to travel one radian in its orbit around the centre of the primary near the pericenter.

While the interaction strength defined with Equation 3 is, indeed, more complete, all of the listed definitions are simplified and have one major caveat. They are all applicable to planar encounters or a simple two-dimensional consideration. In reality, most encounters happen in three-dimensional space - that is, the inclination of the orbit should be accounted for. However, this is not easily solved by introducing yet another measure. By its very definition, interaction strength is a single number with continuous values. This goes against the fact that, during the encounter, the gravitational force could be decomposed into the vertical component and the horizontal one. These components affect the disk-like galaxies in vastly different ways. A single parameter with continuous values would not be sensitive to these different outcomes. Thus, to fully describe the characteristics of an encounter and roughly predict the outcomes, it is most practical to use two numbers - the interaction strength and the inclination.

3. EXAMPLES

Based on the previously discussed matters (the notion of interaction strength and the statistical analysis of cosmological simulation), we conducted research with initial assumptions that the interaction strength determines the outcomes (i.e. not just mass-ratio) and that stronger interactions should be able to induce bar formation in the primary galaxy. We performed 8 simulations, with the typical disk-like galaxy model as a primary and a simple spherical secondary galaxy, scaled to be 10 times less massive (mass-ratio is, thus, $q = 0.1$). While keeping most of the parameters fixed, we varied the impact parameter b following the results of cosmological simulations, which resulted in a range of the interaction strength $0.034 \leq S \leq 0.177$ (for detailed information on models and simulation setup, see Mitrašinović 2022, Mitrašinović & Micic 2023). This range covers weak to strong encounters, all of which are already known to be able to produce spiral arm response, which we confirmed. Thus, in the following examples, we will focus on a phenomenon that appears controversial: bar formation.

We demonstrated that the bar forms early (in addition to the two-armed spiral structure), during or immediately after the encounter, in moderate interactions or stronger, i.e. those with $S \geq 0.076$. In Figure 2, we show synthetic images[2] of an inner disc in the three strongest encounters at three different times after the encounter has ended (i.e. after $t = 1.08$ Gyr). As a direct consequence of the encounter, a short and weak bar can form almost immediately for interaction strengths $S \geq 0.076$. Its initial length appears fairly constant $r_{\mathrm{B}} \sim 3$ kpc, while the strength directly correlates with the interaction strength. Moreover, in stronger encounters, the bar grows quickly and efficiently, both in its length and strength.

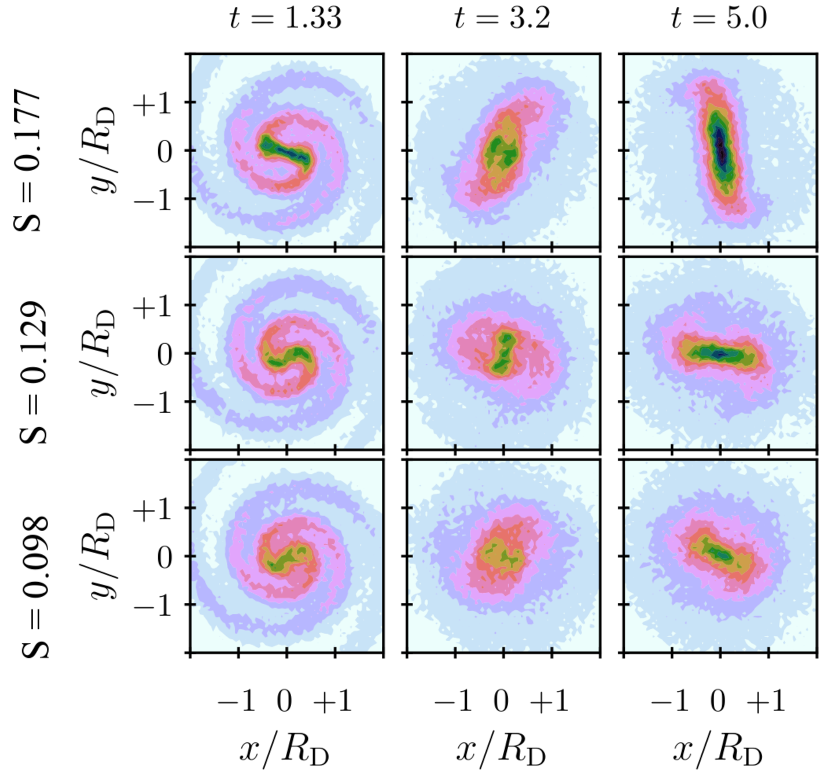

Figure 2: Examples of face-on disc projections (of an inner disc where $R \leq 20$ kpc) in three strongest simulations (top to bottom) at three different times (left to right, given in [Gyr]).

During our analysis, an interesting result has emerged. It appears that some complex morphological features can form during the post-encounter evolution for a range of interaction strengths around $S = 0.129$. In particular, a double-bar feature (also known as *nested bars*), which we showcase in Figure 3. This morphological

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[2] In face-on projection.

structure consists of two bars with their major axes misaligned. Its long-lasting nature stems from the different rotation patterns of the two bars, where the inner one rotates faster. The structure forms after spiral arcs (from the inner parts of a tidally induced spiral structure) have wrapped around an early-formed bar.

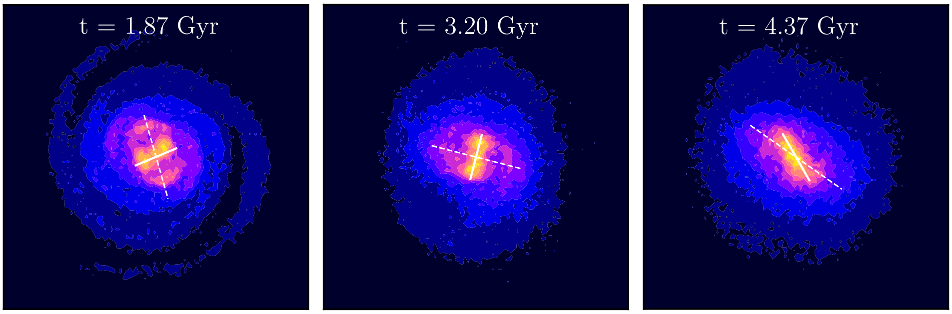

Figure 3: Examples of face-on disc projections (of an inner disc where $R < 20$ kpc) in simulation with $S = 0.129$ at three different times specified on each picture. White solid lines correspond to the major axis of the main bar while white dashed lines represent the major axis of the outer structure. Adapted from Mitrašinović & Micic (2023).

Even though this is out of scope for the current contribution, our results (especially those that are related to complex morphological structures) highlight the necessity for further research on the co-evolution of spiral arms and bars, particularly when both are tidally induced.

4. SUMMARY AND CONCLUSIONS

Considering that galaxy mergers are an integral part of the Standard cosmological model, they are intensely studied, and their classifications are well-defined and widely accepted. At the same time, non-merger encounters have received much less attention, and merger-based classifications have made their way into research focusing on non-mergers. In this contribution, we argue that such a practice is unfounded, as non-mergers are far more subtle, and their consequences depend on various parameters. Moreover, adopting merger-based classifications, where they are not suitable, can lead to conclusions that appear counter-intuitive and misleading.

To support our claims, we first introduced and discussed the concept of interaction strength. We gave examples from our previous research, where we successfully demonstrated that when the interaction strength parameter is properly accounted for, the results are in line with observational implications and theoretical predictions.

While we suggest that non-mergers should be quantified and compared based on interaction strength, we note that such a practice is not always possible in observationally-focused research. However, in theoretical works (for example, cosmological, zoom-in or isolated simulations), similar problems and issues should be non-existent or, at least, marginal and easily solvable. Thus, from a theoretical point of view, approaching a problem with greater care (while keeping in mind all the details, subtleties and nuances) is essential. By doing so, we ensure that the extracted results and conclusions are reliable and robust enough to be compared to observational results. In the end, both approaches should lead to similar conclusions, reaching an agreement if the applied methods and initial assumptions are correct.

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References

An, S.-H., Kim, J., Moon, J.-S., & Yoon, S.-J.: 2019, *ApJ*, **887**, 59.
Elmegreen, D. M., Sundin, M., Elmegreen, B., & Sundelius, B.: 1991, *A&A*, **244**, 52.
Kim, J. H., Peirani, S., Kim, S., Ann, H. B., An, S.-H., & Yoon, S.-J.: 2014, *ApJ*, **789**, 90.
Kumar, A., Das, M., & Kataria, S. K.: 2021, *MNRAS*, **506**, 98.
Lang, M., Holley-Bockelmann, K., & Sinha, M.: 2014, *ApJL*, **790**, L33.
Łokas, E. L.: 2018, *ApJ*, **857**, 6.
Mitrašinović, A.: 2022, *Serbian Astronomical Journal*, **204**, 39.
Mitrašinović, A. & Micic, M.: 2023, *PASA*, **40**, e024.
Oh, S. H., Kim, W.-T., & Lee, H. M.: 2015, *ApJ*, **807**, 73.
Pettitt, A. R. & Wadsley, J. W.: 2018, *MNRAS*, **474**, 5645.
Sinha, M. & Holley-Bockelmann, K.: 2012, *ApJ*, **751**, 17.
Sinha, M. & Holley-Bockelmann, K.: 2015, arXiv:1505.07910.