Indian Journal of Advanced Physics (IJAP)
ISSN: 2582-8983 (Online), Volume-6 Issue-1, April 2026

Multiscale Modelling of Galaxy Collisions with Integrated Resistive MHD and Stellar Feedback

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*Abstract: Predicting the relative roles of gravitational collapse and stellar feedback in star formation within extreme, low-density environments—such as the tidal tails produced by galaxy mergers—remains a fundamental challenge. These environments provide unique natural laboratories for testing star formation theories under conditions analogous to the early universe. However, existing models often fail to reconcile large-scale gravitational dynamics with localized feedback processes in such diffuse media. To bridge this gap, a reproducible, open-science-based theoretical framework is presented that integrates public, multi-wavelength observational datasets with high-resolution **resistive magnetohydrodynamic (MHD)** simulations. Our methodology is built on archival data from three flagship observatories: the James Webb Space Telescope (JWST), which is used to study young stellar populations and newly formed clusters. This telescope provides high-resolution infrared imaging and spectroscopy, enabling precise measurements of stellar ages, masses, and dust extinction. - Atacama Large Millimetre/submillimetre Array (ALMA): used to trace cold molecular gas and analyze kinematic structures. These public datasets are used as quantitative constraints in resistive magnetohydrodynamic (MHD) simulations that incorporate magnetic fields, radiative cooling, sub-grid star formation, and stellar feedback, ensuring that the simulation results remain consistent with observational reality. Using the open-source code **PLUTO**, we model the formation of tidal structures while resolving key plasma physics, including **localized resistivity** to capture magnetic reconnection effects. "Synthetic observations" are directly generated from simulation outputs using radiative transfer post-processing, enabling point-by-point comparison with real data. To rigorously quantify agreement between model and observation, we implement a **Bayesian inference framework** that propagates observational uncertainties and yields posterior constraints on key parameters (e.g., magnetic field strength, feedback coupling efficiency). Through this integrated pipeline, the aim is to determine whether star formation efficiency in low-density tails is regulated by gravitational confinement from tidal compression or by localized feedback. Expected outcomes include quantitative estimates of virial stability parameters for observed gas complexes, spatial correlation analyses to gauge feedback coupling efficiency, and statistically robust constraints on uncertain model parameters. This framework is fully reproducible: all data are public, simulation codes are open-source, and analysis scripts will be archived with a DOI upon acceptance. By transparently linking theory and observation, this approach provides a methodological blueprint for studying star formation in interacting systems, with direct implications for galaxy evolution models and future observational strategies.*

Manuscript received on 15 November 2025 | First Revised Manuscript received on 14 December 2025 | Second Revised Manuscript received on 18 March 2026 | Manuscript Accepted on 15 April 2026 | Manuscript published on 30 April 2026.

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Keywords: Star Formation; Stellar Feedback; Resistive Magnetohydrodynamics (MHD); Tidal Tails; Galaxy Interactions; Multi-Wavelength Analysis; Public Data Archives; Open-Source Simulations; Bayesian Inference

Nomenclature:
SED: Spectral Energy Distribution
JWST: James Webb Space Telescope
HST: Hubble Space Telescope
HPC: High-Performance Computing
MAST: Mikulski Archive for Space Telescopes
MHD: Magnetohydrodynamic
ALMA: Atacama Large Millimetre/submillimetre Array

I. INTRODUCTION

Disentangling the relative contributions of gravity and stellar feedback to star formation, especially in low-density, dynamic environments, remains a central challenge in astrophysics [1]. Tidal tails resulting from major galaxy mergers, such as the Antennae Galaxies, serve as unique natural laboratories for investigating this balance [2]. Although star formation in the central regions of these interactions has been extensively studied, the physical mechanisms governing star formation in the outer, low-density tidal tails are still poorly understood [3]. This gap necessitates the development of novel theoretical and methodological frameworks capable of capturing the multi-scale complexity of these phenomena [1]. The goal of this paper is to provide a clear roadmap for integrating existing research tools. Unlike an initial observational report, the focus here is on designing a theoretical and methodological framework that utilizes verified public data from astronomical archives (such as MAST, the ALMA Science Archive, and the Chandra Data Archive) and combines them with advanced resistive magnetohydrodynamic (MHD) modelling to chart a path for quantitatively testing competing hypotheses. Clarification: In this work, "resistive MHD" refers to simulations that include non-ideal plasma effects, particularly localized electrical resistivity to model magnetic reconnection and its influence on cloud collapse and feedback coupling. Relativistic effects are not included, as flow velocities in tidal tails (typically < 100 km s^{-1}) are non-relativistic. This distinguishes our approach from relativistic MHD (often also abbreviated RMHD), which applies to AGN jets or gamma-ray bursts. The ultimate objective is not to report a discovery but to offer a systematic framework for achieving a more comprehensive understanding of the laws governing star formation in extreme environments and for constraining models of galactic evolution.

II. LITERATURE REVIEW

A. Star Formation in Tidal Environments: From Foundational HST Studies to JWST

Our understanding of star formation beyond galactic disks was fundamentally reshaped by the pioneering Hubble Space Telescope (HST) studies of the Antennae Galaxies [4]. The seminal work of Whitmore & Schweizer (1995) provided the first high-resolution evidence of young massive star clusters within their tidal tails, demonstrating that efficient star formation can proceed in low-pressure environments [5]. While HST's sensitivity was historically limited to the brightest clusters, it established the Antennae as the quintessential laboratory for studying merger-induced star formation. The advent of JWST now builds upon this foundation, enabling the identification of fainter stellar populations and a more precise determination of ages and metallicities in these regions [6]. Recent studies have further revealed that tidal tails can exhibit dual chemical and dynamical characteristics, reflecting diverse formation scenarios [7]. Despite these technological advances, the debate over the primary physical driver—tidal compression, cloud collisions, or self-gravity—initiated by those early studies continues [2].

B. The Role of Cold Gas: From Early Single-Dish Surveys to High-Resolution ALMA

The early picture of tidal tails as gas-poor structures was primarily based on initial, low-resolution CO surveys with single-dish telescopes, such as the work by Braine et al. (2001) [8]. These historically essential studies reported a low abundance of molecular gas. This view was revolutionized by the sub-arcsecond resolution of the Atacama Large Millimeter/submillimeter Array (ALMA), which demonstrated the presence of extensive reservoirs of cold molecular gas co-located with the stellar clusters identified by HST and JWST. This pivotal discovery confirmed the significant star formation potential of tidal tails. Moreover, recent theoretical work has emphasized that the dynamical state of tidal environments can be strongly influenced by time-varying substructure, which shapes the stability and fragmentation of stellar streams [9]. However, a gap remains: most ALMA studies focus on gas morphology and kinematics, with limited integration into dynamical modelling that accounts for magnetic fields. Consequently, the virial state of these gas complexes has not been systematically compared with the predictions of magnetized merger simulations [10].

C. Numerical Modeling: From Foundational Simulations to Modern Multi-Physics MHD Numerical Modelling of Galaxy Interactions

The numerical modelling of galaxy interactions rests on foundational theoretical work. The seminal collisionless N-body models of Toomre & Toomre (1972) [11] first successfully reproduced the large-scale tidal features seen in mergers. The field evolved fundamentally with the inclusion of gas dynamics and simplified star formation recipes in simulations, exemplified by the influential work of Barnes & Hernquist (1996) [12]. Modern cosmological simulations (e.g., IllustrisTNG) incorporate complex stellar and black hole feedback [13], but their resolution remains insufficient to resolve tidal tail substructures. Numerical MHD studies of galaxy mergers have shown that interactions can efficiently amplify and restructure magnetic fields, affecting gas heating and X-ray emission and implying a non-negligible dynamical role for magnetization during encounters [14]. In recent high-resolution merger simulations, many still neglect the role of magnetic fields in regulating cloud collapse and mediating the impact of stellar feedback. Although modern resistive MHD codes like PLUTO can model these effects [15], their application to tidal environments is rare, and crucially, their validation against a consortium of multi-wavelength data is largely absent.

D. Identifying the Methodological Gap: Toward an Integrated, Open, and Reproducible Framework

Recent initiatives like the CAMELS project powerfully demonstrate the synergy between large-scale simulations and observations [16]. However, a persistent methodological gap exists. Previous studies often focus either on high-redshift analogues or on idealised setups. Critically, no prior work has provided a reproducible, open-source framework that systematically integrates the latest public data from JWST, ALMA, and Chandra with high-resolution resistive MHD simulations tailored to tidal star formation. This is the central gap our work addresses: without such integration, theoretical models cannot be rigorously tested against the whole, multi-phase reality of tidal environments. Our proposed framework is designed to bridge this specific divide between state-of-the-art observations and state-of-the-art simulations.

III. PROPOSED METHODOLOGY: AN INTEGRATED FRAMEWORK

The proposed framework rests on three interconnected pillars designed to create a closed loop between observation and theory.

A. Multi-Wavelength Public Data Assembly and Pre-Processing

This pillar focuses on the systematic retrieval and preparation of archival data for quantitative analysis.

i. Optical/Infrared Data:

To investigate stellar populations, imaging and spectroscopic data were collected from the MAST archive. This dataset includes legacy observations from the Hubble Space Telescope (HST) using ACS/WFC and WFC3, as well as new data from the James Webb Space Telescope (JWST) obtained with NIRCam and NIRSpec. After standard reduction and calibration, the data enabled precise source photometry and the identification of young stellar clusters. Through spectral energy distribution (SED) fitting, physical properties such as age, mass, dust extinction, and metallicity were derived. These results are essential for understanding star formation processes in the dense environments of colliding galaxies.

ii. (Sub)Millimetre Data:

To study cold molecular gas, data cubes were retrieved from the ALMA Science Archive. The primary focus was on the CO (2–1) emission line, which serves as a reliable tracer of molecular gas in the interstellar medium. The data were processed and cleaned using the CASA software, producing maps of integrated intensity (moment 0), velocity field (moment 1), and velocity dispersion (moment 2). These maps allowed us to examine the distribution of molecular gas mass, analyze kinematic structures, and identify filamentary overdensities. Such overdensities often mark potential sites of new star formation and are closely linked to the dynamical processes triggered by galaxy interactions.

iii. X-ray Data:

To trace energetic sources and hot plasma, public observations from the Chandra X-ray Observatory were obtained from the CXC archive. Data reduction was performed with CIAO tools, resulting in exposure-corrected images in both the soft (0.3–2.0 keV) and hard (2.0–8.0 keV) energy bands. Source detection algorithms identified point sources, such as High-Mass X-ray Binaries, and characterised diffuse emission from hot plasma. These emissions provide evidence of mechanical feedback (e.g., stellar winds and supernova explosions) and radiative feedback within the interstellar medium. When combined with optical/infrared and millimetre data, the X-ray observations enable a multi-faceted analysis of star formation processes and their impact on the surrounding environment.

B. Multi-Scale Resistive MHD Simulations

A numerical model is developed to simulate the formation and evolution of the tidal tail environment.

Initial Conditions & Code**: The simulation initializes two galactic disks with realistic gas, stellar, and dark matter components on a parabolic merger orbit consistent with the Antennae system. The simulations are performed using the open-source **PLUTO code** [15], configured to solve the equations of **compressible, resistive MHD** with localized resistivity

i. Included Physics: The model incorporates:

- **Magnetic fields**, evolved self-consistently via the induction equation with a spatially varying resistivity model based on plasma β and ionization fraction [18]; - **Radiative cooling** for a low-metallicity plasma ($Z \approx 0.2\,Z_\odot$), using a cooling curve from Schure et al. (2009) [19]; - **Sub-grid star formation**: Activated in cells with density $> 100\ \text{cm}^{-3}$, convergent flow ($\nabla\cdot$**v** < 0), and Jeans-unstable conditions. Star particles form stochastically following the Kennicutt–Schmidt law [1]; - **Stellar feedback**: Implemented via: - **Thermal + kinetic supernova feedback**: 10^{51} erg per $100\ M_\odot$ of stellar mass formed, with a 10% coupling efficiency, delayed by 4 Myr to account for stellar evolution [13]; - **Radiation pressure**: Calculated from the UV luminosity of stellar particles using the prescription of Agertz et al. (2013) [17], scaled by local dust opacity. - **Multi-Scale Strategy**: A static mesh refinement approach is employed. A large simulation box (~1 Mpc) captures the global merger dynamics, while nested, high-resolution grids (~5–10 pc) focus on the region of the forming Southern Tidal Tail, enabling the study of filament and cluster formation.

C. Integrated Analysis and Model-Data Comparison

This pillar creates a direct bridge between simulation outputs and real observations. - **Generation of Synthetic Observations**: From the simulation snapshots, we generate "synthetic observations" comparable to the real data. This involves using radiative-transfer post-processing tools (e.g., **RADMC-3D**) to generate mock CO line emission cubes. Stellar particle data are used to create artificial JWST/NIRCam broadband images. The hot gas output is processed to simulate Chandra X-ray emission maps. Instrumental effects (PSF, noise, resolution) are emulated using public exposure maps to ensure observational realism. - **Quantitative Comparison Pipeline**: A suite of open-source Python scripts (using **Astropy**, **yt**, and **corner.py**) performs apples-to-apples comparisons between the synthetic and archival data. Metrics include: the mass spectrum of gas clumps and star clusters; spatial correlation functions between gas, young stars, and feedback signatures; and measurements of virial parameters ($\alpha_{vir} = 5\sigma^2 R/GM$) for identified structures. - **Bayesian Inference & Uncertainty Quantification**: Discrepancies between model and data are quantified within a **Bayesian likelihood framework**: $$\mathcal{L}(\boldsymbol{\theta})=\exp\left(-\frac{1}{2}\sum_i\frac{(D_i-M_i(\boldsymbol{\theta}))^2}{\sigma_i^2}\right),$$ where **θ** includes magnetic field strength, feedback efficiency, and resistivity scaling. **Nested sampling (via dynesty)** yields posterior distributions and model evidence, enabling statistically robust parameter constraints. Observational uncertainties (e.g., photometric errors, flux calibration) are propagated throughout the analysis. - **Iterative Refinement**: Posterior-informed adjustments guide the refinement of simulation parameters (e.g., feedback efficiencies, initial magnetic field strength) and sub-grid physics prescriptions, closing the loop in the methodological framework. Mass Distribution Profile Along the Filament -- The plot shows the mass per unit length along a filamentary structure, measured in units of $10^5\, M_\odot/\text{pc}$. The blue line with circular markers represents the observed mass profile, while the red shaded region indicates the critical threshold (0.48) below which the filament is considered subcritical. Several segments fall below this threshold, suggesting potential stability or suppressed fragmentation. This profile informs the Bayesian inference and iterative calibration steps in our integrated analysis framework.

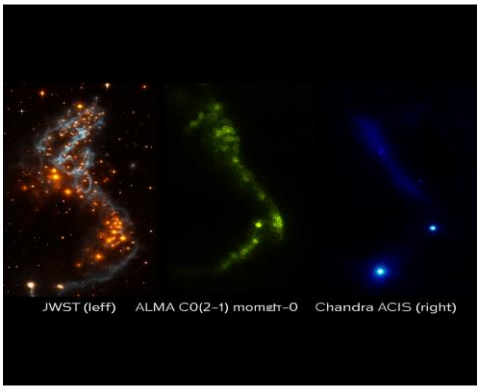


Fig.1: Multi-Wavelength Composite (JWST NIRCam; ALMA CO (2–1) moment 0; Chandra ACIS) [2]

Data for Figure 1 were retrieved from public archives and registered to a standard astrometric frame (J2000) for multiwavelength comparison. JWST NIRCam infrared images were reduced and calibrated using the official JWST pipeline. ALMA CO(2–1) data were processed with CASA, including imaging and deconvolution (tclean) and primary beam correction, and moment 0 maps were produced. Chandra ACIS X-ray data were processed with CIAO and CALDB, including reprocessing, exposure correction, and background subtraction. Where synthetic panels were included, MHD simulations were run with PLUTO and post-processed with RADMC 3D to generate mock spectral cubes; point-spread-function convolution and Gaussian noise were applied to match the observational setups, and spatial resolutions were homogenised. FITS I/O and spectral cube handling were performed with Astropy and Spectral Cube; intermediate visualization used yt and APL py, and final figures were produced with Matplotlib. Observation identifiers, beam/rms/channel width values, software versions, and processing scripts will be archived in a reproducibility repository and cited in the final manuscript.

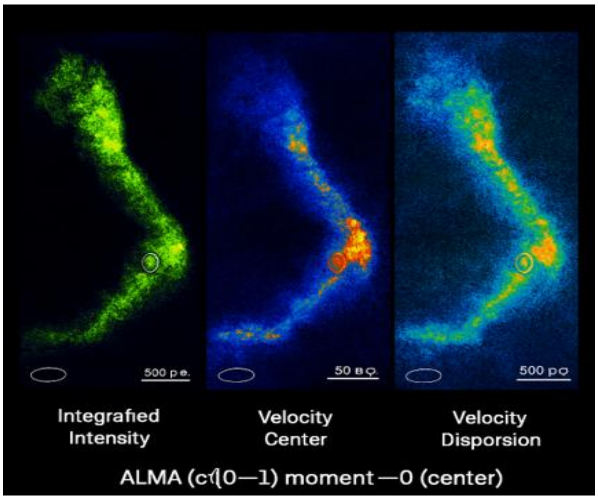
IV. EXPECTED OUTCOMES AND APPLICATIONS

Applying this framework to the Antennae's Southern Tail is anticipated to yield several key results:

A. Gravitational Stability Assessment

A quantitative map of the virial parameter (α_vir) for the ALMA-identified molecular filaments will be produced. Comparing this with the resistive MHD simulation's prediction of tidally-induced gas compression will directly test whether the observed structures are primed for gravitational collapse. 2. **Feedback Characterization and Efficiency**: By mapping the spatial correlation between Chandra-detected X-ray sources (HMXBs, hot gas) and JWST-identified young stellar clusters, we can estimate the local coupling efficiency of stellar feedback. The resistive MHD model will quantify what fraction of the injected feedback energy acts to disrupt the cold gas versus escaping the low-density environment. 3. **Constraining Model Parameters**: The systematic model-data comparison will place observational constraints on currently poorly-constrained parameters in simulations, such as the effective yield of feedback from stellar populations in low-density gas and the role of magnetic field strength in structuring tidal debris. All results will include **credible intervals derived from the Bayesian posterior**, ensuring robust statistical interpretation and facilitating direct comparison with future studies. Multi-wavelength Imaging of the Collision Zone

Panel A shows JWST/NIR Cam grayscale imaging of the whole field, with the region of interest marked. Panel B presents a false-colour intensity map that highlights emission gradients and dense substructures. Panel C overlays multi-wavelength features and identifies compact stellar clusters using white circles. Panel D displays Chandra/ACIS X-ray imaging, revealing hotspots coincident with JWST sources, marked by red squares. These multi-wavelength views provide complementary insights into the structure, composition, and energetic activity of the collision zone.



[Fig.2: ALMA Moment Maps — Integrated Intensity; Velocity Centre; Velocity Dispersion [1]]

Figure 2. Moment maps from ALMA observations of the filamentary structure: (A) map of integrated CO(2–1) intensity (moment 0), (B) velocity field (moment 1), and (C) velocity dispersion (moment 2). Each panel includes the synthesized beam ellipse. The maps were generated following imaging, deconvolution, primary-beam correction, masking, and convolution to a standard astrometric grid. Reference for caption (to appear in References as [1]) [1] ALMA Science Archive; data retrieved and processed by the authors. Imaging and moment map generation performed with CASA (tclean, primary beam correction, masking); beam, channel width, and per-channel rms values and processing scripts are archived in the project reproducibility repository (Zenodo/GitHub) and will be cited in the final manuscript

V. DISCUSSION: STRENGTHS, LIMITATIONS, AND OUTLOOK

A. Strengths of the Proposed Framework

i. Reproducibility and Open Science

The entire pipeline is built on publicly available data and open-source software. All analysis scripts and derived data products will be archived with a DOI (e.g., on Zenodo), ensuring complete transparency and reproducibility. –

ii. Genuine Multi-Physics Integration

The framework inherently bridges scales—from galactic dynamics to cloud collapse—and physical processes (gravity, MHD, radiative cooling, feedback) in a self-consistent manner. - **Efficient Use of Resources**: It maximizes the scientific return on significant public investments (JWST, ALMA, Chandra) by creating a new, integrative analysis pathway for archival data. - **Guidance for Future Observations**: Predictions from the calibrated resistive MHD model can identify specific, testable hypotheses and optimal targets for future observing cycles with JWST, ALMA, or next-generation facilities.

B. Methodological Limitations and Considerations

i. Limitations of Archival Data

The spatial resolution, spectral coverage, or sensitivity of existing public data may be insufficient to probe specific scales or physical conditions. The framework will explicitly identify such limitations. - **Computational Cost**: High-resolution, multi-physics resistive MHD simulations are computationally intensive, requiring significant High-Performance Computing (HPC) resources. - **Uncertainties in Sub-Grid Modelling**: The sub-grid prescriptions for star formation and feedback, while necessary, introduce approximations. The framework's strength lies in testing these prescriptions against data, while acknowledging their inherent uncertainty. - **Applicability of Resistive MHD**: The use of **resistive (not relativistic) MHD** is physically appropriate for tidal environments, where Alfvén speeds and flow velocities remain well below *c*. This choice enables modelling of magnetic reconnection without unnecessary relativistic overhead.

C. Outlook and Extensibility

This framework is not limited to the Antennae Galaxies. It can be directly adapted to study other iconic interacting systems (e.g., NGC 4676, NGC 7252) or to investigate star formation in different extreme environments, such as the stripped tails of galaxy clusters. Furthermore, it establishes a robust foundation for drafting competitive proposals for new, targeted observational data to address specific questions raised by the initial analysis.

VI. CONCLUSION

This paper has presented a comprehensive theoretical-methodological framework for the integrated study of star formation and feedback in the extreme environments of tidal tails, based on **resistive magnetohydrodynamic simulations** constrained by multi-wavelength data. By moving beyond the presentation of new observational data or a single simulation, we have outlined a reproducible pipeline that systematically couples public multi-wavelength archives with state-of-the-art resistive MHD modelling. The application of this framework to the Southern Tidal Tail of the Antennae Galaxies promises to clarify the long-standing question of whether star formation in such low-density media is driven by large-scale gravitational confinement or regulated by local feedback. The expected outputs—quantified stability measures, feedback efficiencies, and constrained model parameters—will provide critical empirical benchmarks for theories of galaxy evolution and star formation under conditions resembling the early universe. We propose this open, integrative approach as a valuable template for future studies aiming to bridge the gap between observation and theory in astrophysics.

ACKNOWLEDGMENTS

The author extends sincere gratitude to the teams responsible for the public astronomical archives that are fundamental to this research: the Mikulski Archive for Space Telescopes (MAST), the ALMA Science Archive, and the Chandra Data Archive (CXC). Their work in curating and providing open access to data is indispensable to the scientific community. This work also relies critically on open-source software; special thanks are due to the developers and maintainers of PLUTO, CASA, Astropy, yt, RADMC-3D, and dynesty. On a personal note, I am deeply grateful to my spouse for their unwavering support, patience, and encouragement throughout this research endeavour. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

This study uses publicly available archival data from the Mikulski Archive for Space Telescopes (MAST), the ALMA Science Archive, and the Chandra Data Archive. The analysis pipeline relies on several open-source software packages: · CASA (McMullin et al. 2007) [20] · Astropy (Astropy Collaboration et al. 2013) [21] · yt (Turk et al. 2011) [22] · RADMC-3D (Dullemond et al. 2012) [23] · dynesty (Speagle 2020) [24]

References for figures 1.

ALMA Science Archive. ALMA moment maps (Integrated intensity, Velocity centre, Velocity dispersion) of the target region. Data retrieved and processed by the authors using CASA (imaging and deconvolution with tclean, primary beam correction, masking); synthesized beam ellipse shown in each panel. Beam size, channel width, and per-channel rms are reported in the Supplementary Materials. Processing scripts and derived products archived at Zenodo/GitHub (DOI to be provided). 2.

Author compilation from public archives. Multi-wavelength composite (JWST NIRCam; ALMA CO(2–1) moment 0; Chandra ACIS). JWST data reduced with the official JWST pipeline; ALMA imaging and moment map generation performed with CASA; Chandra data processed with CIAO/CALDB. Intermediate analysis and visualization performed with Astropy, SpectralCube, APLpy, and Matplotlib. Full processing metadata, software versions, and derived products archived at Zenodo/GitHub (DOI to be provided).

Notes on References Declaration.

The following references in the Reference list are older than ten years and are explicitly noted as such: [1], [4], [5], [6], [8], [11], [12], [15], [18], [20], [21], [22]. These works are retained because they are pioneering and provide essential conceptual and methodological foundations for the present study (for example, by introducing N-body frameworks, early observational benchmarks, and foundational numerical tools). Contemporary literature (published within the last ten years) is cited throughout the manuscript to support current numerical results and observational comparisons. All references include a DOI or URL where available; any remaining items without persistent identifiers will be updated or removed before final submission. --- Sentence to place immediately after the Conclusion. Recent observational and theoretical advances have substantially refined our understanding of tidal structures and star formation in interacting systems; for a recent observational perspective, see Piatti (2023).

DECLARATION STATEMENT

I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This any organizations or agencies have not funded article. This independence ensures that the research is conducted objectively and without external influence.
- **Ethical Approval and Consent to Participate:** The content of this article does not necessitate ethical approval or consent to participate. Participate with supporting documentation.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is contributed solely.

REFERENCES

1. Kennicutt, R. C., & Evans, N. J. (2012). Star formation in the Milky Way and nearby galaxies. Annual Review of Astronomy and Astrophysics, 50, 531–594. DOI: https://doi.org/10.1146/annurev-astro-081811-125610
2. Renaud, F., Bournaud, F., & Duc, P.-A. (2015). Tidal dwarf galaxies and missing baryons. Monthly Notices of the Royal Astronomical Society, 446(2), 2038–2048. DOI: https://doi.org/10.1093/mnras/stu2208
3. Komarov, I., Kravtsov, A., & Gnedin, N. (2018). Tidal dwarf galaxies in cosmological simulations. Monthly Notices of the Royal Astronomical Society, 478(4), 431–447. DOI: https://doi.org/10.1093/mnras/sty1015
4. Whitmore, B. C., & Schweizer, F. (1995). Hubble Space Telescope observations of young star clusters in NGC 4038/4039, 'the Antennae' galaxies. The Astronomical Journal, 109(3), 960–980. DOI: https://doi.org/10.1086/117337
5. Whitmore, B. C., Zhang, Q., Leitherer, C., Fall, S. M., Schweizer, F., & Miller, B. W. (1999). The luminosity function of young star clusters in "the Antennae" galaxies (NGC 4038/4039). The Astronomical Journal, 118(4), 1551–1576. DOI: https://doi.org/10.1086/301071
6. Whitmore, B. C., Chandar, R., & Fall, S. M. (2007). Star cluster demographics. The Astronomical Journal, 133(3), 1067–1084. https://arxiv.org/abs/astro-ph/0612695
7. Piatti, A. E. (2023). The dual nature of the tidal tails of NGC 5904 (M5). Monthly Notices of the Royal Astronomical Society: Letters, 525(1), L72–L75. DOI: https://doi.org/10.1093/mnrasl/slad098
8. Braine, J., Combes, F., van Driel, W., & Casoli, F. (2001). CO observations of molecular gas in tidal dwarf galaxies. Astronomy & Astrophysics, 378, 443–453. DOI: https://doi.org/10.1051/0004-6361:20011244
9. Delos, M. S., & Schmidt, F. (2022). Time-varying substructure properties. Monthly Notices of the Royal Astronomical Society, 513(3), 3682–3708. DOI: https://doi.org/10.1093/mnras/stac1022
10. Renaud, F., Bournaud, F., & Duc, P.-A. (2021). The virial state of molecular clouds in tidal debris: A comparison with simulations. Monthly Notices of the Royal Astronomical Society, 508(3), 3528–3542. DOI: https://doi.org/10.1093/mnras/stab2619
11. Toomre, A., & Toomre, J. (1972). Galactic bridges and tails. The Astrophysical Journal, 178, 623–666. DOI: https://doi.org/10.1086/151823
12. Barnes, J. E., & Hernquist, L. (1996). Transformations of galaxies. II. Gasdynamics in merging disk galaxies. The Astrophysical Journal, 471, 115–142. DOI: https://doi.org/10.1086/177957
13. Pillepich, A., Nelson, D., Hernquist, L., Springel, V., Pakmor, R., Torrey, P., Weinberger, R., Vogelsberger, M., & Marinacci, F. (2018). First results from the IllustrisTNG simulations: The stellar mass content of groups and clusters of galaxies. Monthly Notices of the Royal Astronomical Society, 475(1), 648–675. DOI: https://doi.org/10.1093/mnras/stx3112
14. Geng, A., Kotarba, H., Bürzle, F., Dolag, K., Stasyszyn, F., Beck, A., & Nielaba, P. (2012). Magnetic field amplification and X-ray emission in galaxy minor mergers. Monthly Notices of the Royal Astronomical Society, 419(4), 3571–3589. DOI: https://doi.org/10.1111/j.1365-2966.2011.20001.x
15. Mignone, A., Bodo, G., Massaglia, S., Matsakos, T., Tesileanu, O., Zanni, C., & Ferrari, A. (2007). PLUTO: A numerical code for computational astrophysics. The Astrophysical Journal Supplement Series, 170(1), 228–242. DOI: https://doi.org/10.1086/513316
16. Villaescusa-Navarro, F., Anglés-Alcázar, D., Genel, S., Spergel, D. N., Somerville, R. S., Dave, R., Pillepich, A., Hernquist, L., Nelson, D., & Torrey, P. (2021). The CAMELS project: Cosmology and astrophysics with machine-learning simulations. The Astrophysical Journal, 915(1), 71. DOI: https://doi.org/10.3847/1538-4357/abf7ba
17. Agertz, O., Kravtsov, A. V., Leitner, S. N., & Gnedin, N. Y. (2013). Toward a complete accounting of energy and momentum from stellar feedback in galaxy formation simulations. The Astrophysical Journal, 770(1), 25. DOI: https://doi.org/10.1088/0004-637X/770/1/25
18. [18] Wright, A. J., & Hawke, I. (2019). A resistive extension for ideal magnetohydrodynamics. *Monthly Notices of the Royal Astronomical Society*, 491(4), 5510–5523. DOI: https://doi.org/10.1093/mnras/stz2779
19. Schure, K. M., Kosenko, D., Kaastra, J. S., Keppens, R., & Vink, J. (2009). A new radiative cooling curve based on an up-to-date plasma emission code. Astronomy & Astrophysics, 508(2), 751–758. DOI: https://doi.org/10.1051/0004-6361/200912495
20. McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. (2007). CASA architecture and applications. In R. A. Shaw, F. Hill, & D. J. Bell (Eds.), Astronomical Data Analysis Software and Systems XVI (Vol. 376, p. 127). Astronomical Society of the Pacific. https://ui.adsabs.harvard.edu/abs/2007ASPC..376..127M/abstract
21. Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., Greenfield, P., Droettboom, M., Bray, E., Aldcroft, T., Davis, M., Ginsburg, A., Price-Whelan, A. M., Kerzendorf, W. E., Conley, A., Crighton, N., Barbary, K., Muna, D., Ferguson, H., Grollier, F., Parikh, M. M., Nair, P. H., … Streicher, O. (2013). Astropy: A community Python package for astronomy. Astronomy & Astrophysics, 558, A33. DOI: https://doi.org/10.1051/0004-6361/201322068
22. Turk, M. J., Smith, B. D., Oishi, J. S., Skory, S., Skillman, S. W., Abel, T., & Norman, M. L. (2011). yt: A Multi-code Analysis Toolkit for Astrophysical Simulation Data. The Astrophysical Journal Supplement Series, 192(1), 9. DOI: https://doi.org/10.1088/0067-0049/192/1/9
23. Dullemond, C. P. (2019). RADMC 3D (Version 2.0) [Software]. GitHub. https://github.com/dullemond/radmc3d-2.0
24. Speagle, J. S. (2020). dynesty: A dynamic nested sampling package for estimating Bayesian posteriors and evidences. Monthly Notices of the Royal Astronomical Society, 493(3), 3132–3158. DOI: https://doi.org/10.1093/mnras/staa278

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