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## A Coupled Oscillator Approach to Energy Dissipation due to Tidal Forces in Cosmology

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**Abstract.** The coupled oscillator approach is very useful for modelling exoplanet interiors, galaxy cluster mergers and compact binary spirals. In this study, a simplified two-coupled oscillator model to quantify energy dissipation due to linear tidal forces is developed and its implications for cosmic evolution explored. The model incorporated gravitational and tidal interactions and the equations of motion of the system is derived using Lagrangian mechanics with dissipative terms which made it easier to treat tidal dynamics as solvable mechanical systems. The model also predicts dissipation rates for orbits, spins and deformations and links microphysics to macroscale evolution.

**Keywords:** coupled oscillator, energy dissipation, tidal dissipation, gravitational interactions, cosmic evolution, galaxy cluster mergers

**Introduction.** In cosmology tidal forces are caused by the differential gravitational pull on an object in a non-uniform gravitational field and these forces are important in the dynamics of galaxies clusters, and other cosmic structures such as binary star systems, exoplanetary systems and black hole mergers. These forces can lead to energy dissipation through mechanisms like tidal friction and heating, influencing the evolution of cosmic systems [1, 2]. Observations of clusters of galaxies of different sizes showed that they are bright x-ray sources whose emission mechanisms is thermal bremsstrahlung from hot low density gas [3, 4]. There are already a deluge of theoretical and experimental studies investigating tidal forces and energy dissipation in cosmology [5, 8]. In this current study, we have developed a simplified two-coupled oscillator model to quantify energy dissipation due to linear tidal forces and explore its implications for cosmic evolution. Further, we have incorporated gravitational and tidal interactions and derive the equations of motion using Lagrangian mechanics with dissipation terms.

**Methods and materials; results.** For the simple model of two body system (body 1 and body 2) proposed here we treat the interacting cosmic bodies such as a star and a planet or two galaxies, as mass-spring-damped systems at distance  $d$ , we shall adopt the Lagrangian mechanics-based approach for coupled damped har-

monic oscillators [4] in which we incorporate into the Lagrangian of the system the gravitational coupling between two oscillators representing the cosmic bodies of masses  $M_1$  and  $M_2$ , and the tidal dissipation is represented by the dampers  $\gamma$ . The tidal forces will be treated as perturbations such that the deformation of body 2 is due to the gravitational gradient of body 1.

Now, the modelling approach is that the tidal forces lead to energy dissipation through mechanisms such as the internal friction generated by the relative motion of different parts of an object, the conversion of mechanical energy into heat due to tidal deformation and the energy loss in fluid components, for example the gas in the galaxies or clusters, due to viscosity. After some slightly rigorous mathematics, we obtained expressions for the energy dissipation, instantaneous power loss and the time-averaged dissipation for circular orbits with frequency.

Results: The model was also applied to study binary star synchronization by modelling tidal locking timescales and also explain the observed rotational frequency and orbital frequency ratio distributions in previous studies [8, 9]. Work is still in progress on how the model would be applied to study galactic flyby interactions such as estimate tidal stripping rates in dwarf galaxies and to predict star formation triggers from tidal heating.

**Conclusion.** The coupled oscillator model developed here is a simplified framework for studying tidal dissipation in cosmology, linking microphysical processes to macroscopic. The results obtained from the application of the model compares with astrophysical observations such as orbital circularization in binary stars and tidal heating in exoplanets. It is recommended that this work be improved by introducing general relativistic corrections. Here, we considered for simplification only two coupled oscillators, for hierarchical structure formation, multi-oscillators may be considered.

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