Starburst triggered by compressive tides in galaxy mergers

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Received 20 August 2008

Key words galaxies: individual (NGC4038/39) — galaxies: evolution — galaxies: interactions — galaxies: starburst — galaxies: star clusters — stars: formation

The tidal field of galaxies is known generally to be disruptive. However, in the case of galaxy mergers, a compressive mode of tidal wave may develop and last long enough to cocoon the formation of star clusters. Using an N-body simulation of the Antennae galaxies, we derive the positions of these compressive regions and the statistics of their duration. Excellent agreement between the spatial distribution of tides and observed young clusters is found, while the characteristic e-folding times of 10 to 30 Myrs derived for the tidal field compare well with cluster formation time-scales.

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1 Introduction

It is well known that gravitational tides work to disturb or even destroy galactic disks and substructures. However, one should not forget that tidal fields can also be compressive and have the opposite effect. For example, the tidal force perpendicular to the line connecting two spherical mass distributions is compressive. Moreover, for specific mass distributions, the tide can be compressive in all directions (e.g. Valluri 1993). When that is the case, a tidal force will work to gather matter and keep it bound. A picture emerges from such considerations whereby e.g. a molecular cloud experiencing a compressive tide for a long-enough time would collapse, form a cluster of stars, and keep the gas in the vicinity of the proto-cluster: stars would form even in a collapse, form a cluster of stars, and keep the gas in the vicinity of the proto-cluster: stars would form even in a globally low star formation efficiency environment. Furthermore, their feedback (e.g., stellar winds or radiation) would not affect the cluster as much as if it were in isolation (Elmegreen \& Efremov 1997), owing to additional binding energy. It is possible that this effect would significantly alter the mass-loss process which likely affects the late stage of the formation of star clusters (e.g. Bastian \& Goodwin 20-06). A cluster which forms within a compressive tidal field would be super-virial after it relaxed to equilibrium, and thus would re-expand or even dissolve whenever the tide switches from a compressive, to an extensive mode. This could be a clue to understand the process driving the rapid dissolution (or, “infant-mortality”) often invoked in relation to the demographics of young clusters in the Antennae galaxies (Whitmore et al. 2007).

Our goal here is to show that compressive tidal modes are effectively operative on a cluster-formation time-scale. It is therefore likely that clusters are super-virial in their infancy but are prevented from dissolving by the background tide. After a brief presentation of compressive tides, we present an N-body model of the Antennae galaxies and the statistics of their tidal field.

2 Tidal tensor and compressive tides

Tides are usually evoked for their destructive effects. In the case of the merger of two spiral galaxies, tidal bridges and tails commonly form from the extension of the disks material. This disruption can be described by the tidal tensor

\[ T^{ij} = -\frac{\partial_i (\partial_j \phi)}{} \]

where \( \phi \) is the gravitational potential. Because of its symmetry, it can be set in an orthogonal form. Its eigenvalues then represent either a compression (if negative) or an extension (if positive) along the corresponding eigenvector. Consequently, inspection of the sign of the maximum eigenvalue allows to distinguish between fully compressive and extensive modes.

For the logarithmic potential

\[ \phi_{\log}(x) = V_c^2 \ln \sqrt{1 + \frac{x_k x^k}{b^2}} \]  

(we apply Einstein’s summation convention), the tidal tensor reads

\[ T^{ij}_{\log}(x) = -\frac{V_c^2 \delta^{ij} \left( b^2 + x_k x^k \right) - 2x_i x_j}{\left( b^2 + x_k x^k \right)^2} \]

and produces compressive tides when \( \sqrt{x_k x^k} = r < b \), i.e. in the inner part of the potential. Adding a second, similar potential (same parameters, as for a major galaxy merger) shifted along the vertical axis, we show on Fig. \( \text{I} \) (right panel) how the compressive regions (red on the figure) covers a larger volume than for a potential taken in isolation (left panel on that figure).
Fig. 1  Totally compressive (red) and extensive (blue) tidal regions for the logarithmic potential in isolation (left-hand panel), and for two identical logarithmic potentials, but one shifted by $\sim 2b$ units along the vertical axis (right-hand panel).

Fig. 2  Column density of the N-body model of the Antennae galaxies and a zoom-in on the central region ($\sim 40$ kpc wide) at the present time (300 Myr after the first pericenter passage).

3 The Antennae

We applied the tensor analysis to an N-body simulation of the Antennae galaxies (NGC4038/39). As we consider the gravitational field only, no gas was included in the simulation. This model uses an S0 and an Sa progenitors, each made of an exponential disk, a Hernquist bulge and an isothermal dark-matter halo (see Renaud et al. 2008 for more details). The progenitor galaxies have a mass ratio of 1:1 for a total mass (stars + dark matter) of $\sim 9.2 \times 10^{10}$ M$_\odot$. The galaxies were set on a prograde elliptical orbit ($e \approx 0.96$) with an initial separation of 75 kpc. We obtained a good match to the observations, both in terms of morphology and the velocity field, some 300 Myr after the first pericenter passage (Fig. 2). The mass resolution of $\sim 2 \times 10^5$ M$_\odot$ means that a single particle is a cluster-size element.

We extracted the tidal tensors of all 400,000 disks particles for a large sequence of simulation snapshots to achieve a time-interval as low as 2.5 Myr. Fig. 3 plots the fractional number of particles (in percentage) in a compressive tidal field as a function of time. During the early stages of the merger, the mass fraction stays at a level of 3% (as for each progenitor taken in isolation) until it suddenly increases at the first pericenter passage (peaks A and B). The fraction rapidly drops and almost returns to its initial value as the system re-expands and the progenitors move apart. However, it rises again by a factor $\sim 5$ at the second passage (peaks C and D, the current time, labeled ‘now’). Note that this increase compares well with typical star formation rates obtained from hydrodynamical simulations of starburst models with similar setups (see Di Matteo et al. 2008). We conclude from the simulation run that stars and star clusters formed $\sim 300$ Myr ago are to be linked with the first pericenter passage and the creation of the two tidal tails.

Fig. 4 maps the position of these compressive regions at the present time (peak D on Fig. 3) to the Antennae galaxies. The background is a composite HST/VLT image adapted from Mengel et al. (2005), showing the nuclei and the overlap region. Note the good match between the particles in compressive mode and the sites of cluster formation, mainly on the bow shape around the northern nucleus (where north is up) and in the overlap region, between the two cores. This is a good hint that the tidal field plays an important role in the formation of such stellar structures.

To backup this idea, we plot on Fig. 5 the mass fraction in compressive modes as a function of their duration. We show that about 55% of the disk mass experience a continuous tidal compression lasting longer than 10 Myr. These figures overlap with age estimates of young clusters of the Antennae, and thus emphasize the role of the compressive tidal mode in the formation of these systems.

4 Conclusions

Using a gravitational N-body simulation of the Antennae galaxies, we derived the statistics of cluster-size elements
Fig. 4  Spatial distribution of the compressive regions in the central part (red dots), laid over an optical image of the Antennae (grey scale background, adapted from Mengel et al. 2005). The data points displayed correspond to the current time (peak D on Fig. 3).

experiencing a tidal compression. The results show a good match with observational data, both in terms of spatial distribution and characteristic times. The statistics of tidal field evolves rapidly as the number of compressive regions increases by a factor 5 during the merger. The characteristic duration of compressive modes and their spatial distribution suggest that they play an important role for the formation of clusters, as they would keep them bound and prevent or delay their rapid dissolution. A follow-up study will explore the response of gas on a cluster scale when considering the external tidal field as boundary conditions.

Acknowledgements. FR acknowledges a scholarship from the IK1033-N Cosmic Matter Circuit at the University of Vienna. CT is grateful to the German Science Foundation (DFG) for financial support within the priority program 1177.

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