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Gas Flow and Star Formation in the 'Antennae' Galaxies

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Abstract.
The prominent interacting galaxy pair NGC 4038/9 contains many active star-forming regions and is continuously forming new star clusters. We present a self-consistent n-body model for this system which includes an SPH gas component. The model qualitatively explains the apparent concentration of gas in the so-called overlap region *between* the two nuclei as a bridge of gas connecting the two galaxies. Projected on the sky, the bridge appears as a dense spot of gas. We discuss some implications for the evolution of Ultra-luminous infrared galaxies.

The stellar dynamics of the Antennae galaxies merger has been studied in detail by Toomre & Toomre (1972), Barnes (1988), and others. We are interested in this merger to study star formation under extreme conditions. The gas transport towards the galaxy centers in the early stages of the mergers may lead to circum-nuclear starbursts. Tidal forces during the first passage trigger the formation of bars or induce $m = 2$ spiral arm modes in the approaching galaxies. Once a bar is forming, the gas piles up at the inner Lindblad resonance which in turn undergoes rapid star formation. The distribution of young stellar clusters, is therefore linked to the dynamical history of the merger.

With bolometric luminosities and space densities comparable to or even higher than those of quasars, Ultra-luminous Infrared Galaxies (ULIRGs) are the most luminous objects ($L \geq 10^{12} L_\odot$) in the local Universe (Soifer et al. 1987). Deep ground based (Rigopoulou et al. 1999) and HST–NICMOS (Scoville et al. 2000) images reveal that ULIRGs are undergoing a major merger. Often the merging includes two similar size disk galaxies. However, the merging sequence for ULIRGs seems to be somewhat different from that of lower luminosity nearby mergers, implying that perhaps ULIRGs have a different type of progenitor galaxies or their gas properties are different.

Rigopoulou et al. (1999) have shown that in fact the gas properties of ULIRGs are different than those of the less luminous ($L \geq 10^{11} L_\odot$) LIRG systems. They found that although in LIRGs the CO content decreases with decreasing separation, ULIRGs appear to still be gas-rich even at advanced stages of the merger. Activity in ULIRGs is known to be in part due to star bursts and also due to AGN activity. One may speculate, that AGN activity is triggered by the merger event. However, no correlation between AGN activity and merger state has been found (Rigopoulou et al. 1999). To explain such results we have embarked into a project in investigating whether the ULIRG progenitor galaxies are more stable against bar formation than other mergers (Mihos & Hernquist 1996) e.g. due to a stronger bulge component.

While not being ULIRGs themselves, the Antennae galaxies provide an excellent starting point for studying ULIRGs. As a first step, we model the Antennae system as closely as possible to explain gas distribution and present star formation rate. A nice goal is to reproduce the observed distribution of young star clusters, which are concentrated towards the so-called overlap region and also follow some spiral arm structure. Our model presented here is similar to the model by Barnes (1988), but in addition includes a gaseous component. The n-body representation of both galaxies consists of four components. The mass ratio for bulge:disk:halo:gas is 1:4:23:0.8. The total number of particles is 100'000 (30'000 in gas). The gas is treated as a single component SPH gas initially distributed in a constant surface density disk. No attempt has been made to improve the orbital parameters, as the match between the observed and modeled distribution of stars is already quite good. Star formation in the code is turned off.

The overlap region, where the two disks appear to overlap in projection, corresponds in the model to a bridge between the galaxies formed by $\sim 20\%$ of the gas and $\sim 30\%$ of the stars. The gas fraction is likely to increase when an exponential gas disk is used. In fact, both galaxies are distorted by tidal forces into bars aligned with each other in such a way that they form a connected V-shaped structure with the kink in the overlap region. Observations indicate a large amount of gas, dust and ongoing star formation in this region (Whitmore et al. 1999; Mengel et al. 2000). From the time sequence of our merger simulation, we conclude that the gas in the overlap region originates mostly from inside the disk region where the bars are formed by tidal forces. But some gas also comes from the region which was compressed first in the collision between the two disks, i.e. from larger disk radii.

Since the formation of the bars further amplifies the compression, it may not be surprising that most young star clusters are found in that area. When seen from the side, the gaseous bridge is offset by a few kpc from the stellar bars. In the model this is the time when the separation between gas and stars is largest. To understand the formation of clusters in detail, a more realistic model for the gas is required. Most likely, clusters are formed out of giant molecular clouds which collapse from overpressure generated by the starburst (Jog & Solomon 1992). Therefore the number of star clusters formed will also depend on the properties of the in falling galaxies.

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