THE MORPHOLOGY OF AND LOCATIONS OF STAR FORMATION IN IMPACT INDUCED RING GALAXIES

by

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Observed ring galaxies appear to fall into two major types. The first tends to consist of isolated galaxies which display a smooth, apparently circular ring and a central nucleus. These have been variously classified as R(S) by de Vaucouleurs (1959) and as type O by Few and Madore (1986). The second class of ring galaxy nearly always has a close companion of comparable size (no less than about one tenth that of the ring galaxy). In these objects the ring is knotty in appearance, is usually elliptical, even when deprojected on the sky, and is often open on one side, having a 'horse shoe' or 'banana' shape. The nucleus does not usually appear at the center of the ring and is sometimes apparently absent, giving rise to an 'empty ring' galaxy. deVaucouleurs et al. (1976) designated this second type as RING, while Few and Madore (1986) have classified similar galaxies as P type. These galaxies have elevated far IR emission, bright HII regions, and blue spectral colors. The different environments of the two types or ring galaxy, together with their overall morphological and spectral differences suggest that the R(S)/O type are most probably the result of an instability that occurs in isolated galaxies, whereas the RING/P type appears to be the result of a recent collision between two roughly equal mass objects, at least one of which is a disk galaxy. Theys and Spiegel (1976) studied a sample of this latter type and identified three subclasses: RE: galaxies with crisp, empty rings; RN: galaxies like those of RE but with off-center nuclei; RK: galaxies having single dominant knots or condensations in the rings. A presentation of a preliminary understanding of the connections between these different observed forms in terms of parameters which are intrinsic to the galaxy system, such as time since collision and impact parameter, and in terms of our line of sight view is the purpose of this paper.

Here we report results we have obtained from three dimensional computer simulations of collisions between equal mass galaxies, one of which is a rotating, disk galaxy containing both gas and stars and the other is an elliptical containing stars only. We have used a combined n-body/SPH program (see Balsara,1990) to model fully self consistent models in which the halo mass is 2.5 times that of the disk and gas comprises ten percent of the disk mass.

In the experiments we have varied the impact parameter between zero (head on) and 0.9R (where R is the radius of the disk), for impacts perpendicular to the disk plane (see Gerber, Lamb, and Balsara, 1992b) and obtain a full ring (for head on collisions) or a partial ring (for off-center collisions), in both the stars and the gas. The results of our simulations, which cover a time period approximately equal to the dynamical time scale of the collision (typically a few times 10^8 years), when viewed from different lines of sight allow us to understand the gross connections between the different forms observed in RING/P type galaxies. For example, we find that:

1) The nucleus of the disk galaxy is always displaced out of the plane of the disk in the direction of travel of the elliptical and also that it will be offset from the center of the partial ring for off-center collisions. These two effects combine for off-center collisions to result in the nucleus appearing 'buried' in the ring for a non negligible range of viewing angles, thus leading to a natural explanation of the RE type of ring galaxy. In order to observe this effect, the disk plane must be tipped to the line of sight, and we expect that a viewing angle near $45°\pm15°$ would be optimal. A more face on view would reveal the nucleus to be distinct from the ring or arc and a more edge on view makes it hard to identify ring or arc structure in the galaxy. An example

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of a ring galaxy with an embedded nucleus is Arp 147. This object has been observed optically by, among others, Theys and Spiegel (1977) and more recently in the ultraviolet by Schultz *et al.* (1990) using the IUE satellite. In a recent paper, we were able to obtain a reasonable fit to the observed morphology and velocity data of this system (see Gerber, Lamb, and Balsara,1992a) using one of the off-center simulations discussed above.

2) The outwardly propagating ring or arc of excess density in the gas interacts with outer, infalling material to produce regions of shocks and dense gas, thus providing a region primed for star formation. In a head-on collision, the density wave moves outward as a ring; however, in off-center collisions the location of the densest regions has a more complicated history. In these latter cases, local maxima occur in the density of the disk at the impact point and at the nucleus at the time of impact. As the collision evolves the density at the nucleus diminishes somewhat due to the overall expansion of the disk galaxy subsequent to the impact; the density maxima at the impact point is spread into an arc by the differential rotation of the disk and develops several regions of high density within the arc structure. A typical configuration observed in several galaxies consists of two regions of high density in the arc, somewhat symmetrically situated on either side of the nucleus. Our numerical experiments show that this is a transient phenomena due to the combined effect of differential rotation in the disk, the expansion of the inner disk following the collision, and the continued infall of the outer disk. The one high density 'wing' is the remnant of the density enhancement produced at the impact point and the other is the result of strong collisions between infalling and expanding disk material.

3) As the ring or arc ages it becomes more diffuse and may tend to clump further.

4) More off-center collisions produce, among other things, more open arcs.

5) Regions of high volume gas densities do not necessarily coincide with regions of high surface gas densities. In many of our models the surface density, integrated along a given line of sight, peaks in the nucleus of the galaxy even though the volume gas density is greatest in the ring or arc. For this reason measured values of gas surface density alone may not be adequate for predicting the occurrence and quantity of star formation.

We conclude by stressing that those ring galaxies produced by collision provide a unique laboratory for the study of star formation in disturbed galaxies. The apparent sequential star formation identified by Appleton *et al.* (1991) and others can be understood in terms of the evolution of the high density structures produced by the collision. Thus, an experimental understanding of the evolution of the ring or arc structure for different collision parameters, together with an exploration of possible viewing angles, allows us to sequence observed galaxies and to thereby understand the star formation histories, not just for one system, but for galaxies of this general type.

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