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STARBURSTS IN COLLISIONALLY PRODUCED RING GALAXIES: COMPARISONS BETWEEN NUMERICAL MODELS AND OBSERVED SYSTEMS

Susan A. Lamb[1], Richard A. Gerber[2], Gregory H. Rudnick[1], and Mark Dewing[1]

RESUMEN

Las "galaxias de anillo" producidas por colisiones, usualmente muestran formación estelar vigorosa en arcos o anillos de gas en expansión. Este modo de formación estelar domina la apariencia óptica de las galaxias y las imágenes en el cercano IR muestran que la población estelar del disco también es arrastrada por una onda de densidad que se expande y que está ligeramente desplazada respecto al anillo. La apariencia óptica muestra que la formación estelar de los anillos se da en condensaciones a lo largo de ellos. Se comparan datos de dos galaxias, tomados de la literatura, con modelos numéricos tridimensionales. Esta comparación da información muy valiosa sobre las escalas de tiempo y la dinámica global de la colisión, así como sobre la formación estelar global propagada por ondas de densidad.

ABSTRACT

Collisionally produced "ring-galaxies" usually display vigorous star formation in an expanding ring or arc of high density gas. This star formation dominates the appearance of these galaxies in the optical while near-IR images show that the older stellar disk population has also been swept into an outwardly expanding density/material wave which can be slightly displaced from the gas ring. A dominant feature of the optical appearance of many of these ring-galaxies is the clumpy nature of the star forming regions along the arc or around the ring of gas. We compare data from the literature on two of these galaxies with detailed numerical three-dimensional models. The comparison of models with real systems gives valuable information on timescales and on the global dynamics of the collision, as well as insight into the factors which determine the characteristics of global star formation in these and other density wave driven star forming regions.

Key words: **GALAXIES: INTERACTIONS — HYDRODYNAMICS — INSTABILITIES — STARS: FORMATION**

1. INTRODUCTION

The dominant stellar rings and partial rings which are observed in the disks of some galaxies, have been shown to have a dynamical origin and are caused by collision with another galaxy of comparable or somewhat smaller mass. Here we use the observations available for two classical blue ring galaxies, LT41 and IIZw28, to constrain suitable dynamical models. Using these model fits we can understand some aspects of the star formation histories in the rings and make predictions about future observations. The models are chosen from a grid of simulations produced by Gerber, Lamb, & Balsara (1996, 1997) which explore the results of face-on collisions between an elliptical and a disk galaxy. The mass ratio between the two is varied between 1:1 and 1:10, respectively, and the impact parameter ranges from zero (head-on) to slightly larger than the disk radius.

2. COMPUTATIONAL METHOD AND GALAXY MODELS

The experiments are comprised of combined N-body/Smooth Particle Hydrodynamic, 3-D numerical simulations of collisions between a rotating disk galaxy, composed of gas, stars, and dark matter, with a spherical galaxy composed of stars and dark matter only. The gas dynamics is modeled numerically using the method of smoothed particle hydrodynamics (SPH) and both the stellar and SPH particles contribute to the gravitational potential. In the simulations employed here we use a cubic grid with 64 points along

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[1] University of Illinois at Urbana-Champaign, USA.

[2] Space Science Division, NASA Ames Research Center, USA.

each side. More details of the combined code can be found in Balsara (1990) where tests of it are presented All computations were performed on the Cray-2 supercomputer at the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign.

We used a King model to represent the stars and dark matter of the elliptical. It is spherical and gasless and can be thought of as an E0. The model for the halo of stars and dark matter in the disk galaxy was also produced from a King model. The disk has a mass two fifths that of the halo and is comprised of both stars and gas, the latter having one tenth of the disk mass. The disk galaxy can be thought of as an Sc. Approximately 22 000 SPH particles are used to model the gaseous disk and they are initially placed in circular orbits around the center of the disk. The gas density distribution follows that of the disk stars. The disk and halo of the disk galaxy are each represented by 25 000 (N-body) particles, whereas the intruder is represented by 10 000 particles.

We incorporate a simplified representation of the gas in which only one phase is modeled. The gas density in the plane varies between 0.025 amu/cc and 2 amu/cc, and its temperature lies in the range of 8000 K to 6×10^5 K. It is assumed that the gas is isothermal, that is, that the time scale for radiation processes tha cool the gas behind shock fronts are shorter than the calculational time step. Full details of the computationa method and the starting models can be found in Gerber (1993).

3. LT41 - A LARGE RING GALAXY WITH AN ELLIPTICAL INTRUDER COMPANION

The galaxy LT41 was first identified as a dynamical ring galaxy by Thompson (1977). LT41 is one of the most distant, with z = 0.09 (a Hubble constant of 75 km s^{-1}/Mpc gives a distance of 286.6 Mpc), collisionally induced ring galaxies that have been investigated and this fact, together with the angular size of its ring of approximately 18″ x 13″, implies large linear ring dimensions of 25 Kpc × 17 Kpc. The very large size of this ring indicates that the collision is now well advanced. Using the dynamical model proposed below and model scaling implied by using the K-band derived mass (see Marston & Appleton 1995, hereafter MA95) of $6.98 \times 10^{10} M_{\odot}$, we obtain the result that the closest approach between the nuclei of the target disk galaxy and the intruding elliptical occurred approximately 1.5×10^8 years ago.

Both the ring galaxy and the companion show up well in the K-band image of MA95. The flux in this wavelength band is most closely connected to the radiation from the older stellar population, the one that existed prior to the collision, and is thus that most directly related to the mass of luminous matter in the galaxy. Using their observed flux MA95 derive an old stellar disk mass of $6.98 \times 10^{10} M_{\odot}$ for the ring galaxy (approximately that of the Milky Way). Their K-band image of the system implies that the intruder has a comparable or slightly larger mass. For this reason we have chosen to fit the observations with a model of equal mass galaxies.

MA95 find that the Hα emission is essentially all confined to the ring, very little coming from either the nucleus or the companion,and that this emission is smooth except for two emission knots. We use this fact to confirm the age of the collision and to put a restriction on the impact parameter. We find that the best model fit is obtained for equal mass galaxies in which the impact parameter was roughly 0.4 times the initial disk radius (Gerber, Lamb, & Balsara, 1997). This translates into an approximate separation of 3.2 Kpc for LT41 The best fit to the described observational data and constraints is obtained if we view the model system from an angle of 51 degrees to the disk normal.

During the collision process there is a migration of the peak gas density around the dense arc structures produced by slightly off-center, face-on collisions. That is, the highest density in the arc is initially at the location closest to the point of impact of the intruder. Then, as the structure evolves, the density peak splits and two density peaks move towards the 'horns' of the arc. From the models we find that the high density regions are also the locations of strong shocks in the gas. Assuming that high gas density and the presence of shocks is conducive to star formation, these models predict that new star formation will also migrate around the arc structures, as has been demonstrated for Arp 147 (Gerber, Lamb, & Balsara 1992). The remnants of the very high star formation rates in a ring or arc at an earlier epoch should show up as an enhanced B-band flux around the ring and a gradient around the ring in the average age of the young stars. Appleton & Marston (1996) found that the B-band flux is large around much of this ring with a particularly high intensity in one region, indicating that the intruder went through the disk on that side of the nucleus.

The simulations show that gas becomes clumped around the ring as it evolves. These clumps are resolved in our computations and thus have a scale of around 500 pcs or larger. It is tempting to make a connection between these high density regions and the large, luminous regions of star formation observed in many ring galaxies LT41 is very distant and the current resolution limit does not allow observations in Hα on this scale. We predict that when such observations are performed the clumpy nature of the Hα distribution will be detected.

4. IIZW28 - A SMALL RING GALAXY WITH NO INTRUDER CLEARLY IDENTIFIED

The blue ring galaxy IIZw28 was first well studied as a dynamical ring galaxy by Theys & Spiegel (1976) who classified it as a ring with one dominant knot or condensation in the ring. However, Marston & Appleton (1995) have now observed detailed structure in this ring. It is at a distance of 113.8 Mpc and the angular size of the ring is $13'' \times 11''$ giving an approximate linear size of 7 kpc. Such a small diameter ring in a galaxy with the mass of IIZw28 implies a moderately low dynamical age for the ring structure. Even with the lowest possible plausible galaxy mass the ring is still inside the original disk radius. The apparent lack of an obvious nucleus is consistent with this being a dynamically young object in which the ring has not yet had time to evolve far from the nucleus. The dominant, bright knot seen in R- and K-band images (see, Appleton & Marston 1996) then attributed, at least in part, to emission from the nucleus. The almost full, slightly elliptical ring shows a slight morphological asymmetry between the west and east sides of the ring which is characteristic of face-on, somewhat off-center collisions (see, Gerber & Lamb 1994; Gerber, Lamb, & Balsara 1996).

The lack of an identified intruder galaxy complicates the choice of a model fit to this galaxy. The most likely possibility is that we are viewing the intruder superimposed on the ring and that its emission contributes to the bright condensation. In exploring models to fit this system we investigated both equal mass collisions and those in which the intruder has a mass one quarter that of the disk galaxy. The higher mass intruder appears to be preferable as this simulation produces a higher density ring and distinct clumping in the gas around the ring, as discussed above for LT41. This gives a better fit to the detailed observations of the IIZw28 ring structure. However, for both mass ratios, we find that an off-center collision with an impact parameter of approximately 0.4 times the disk radius gives the best fit to the observed asymmetric arm structures and the location of the nucleus. The model gives a best fit when viewed from an angle of 23 degrees to the galaxy normal; the intruder then appears superimposed on the ring. Scaling the simulations to the K-band mass of this galaxy, this model corresponds to a time of approximately 1.15×10^8 years after closest approach of the two galactic nuclei.

A study of the simulation sequence from which our model fit was obtained indicates how the three dense Hα knots observed around the ring were likely formed by migrating density peaks, as discussed above. One knot is at the location of the strong condensation seen in the R- and K-bands, that is, at the peak in the continuum emission, and the other two are displaced in each direction from this around the ring. We predict that the average age of the massive stars in the central knot is larger than that in the two side knots. Postscript versions of the figures of the numerical models for the IIZw28 and LT41 systems are available from Susan Lamb at s-lamb1@uiuc.edu.

5. CONCLUSIONS

In general, high volume densities are obtained in the gas at the same locations that shocks occur. If we assume that star formation in these galaxies is triggered in such regions, we can predict the locations of the intense bursts of star formation observed to occur in these galaxies. The volume density in the gas ring can increase by up to a factor of about 100 while the surface density increases in this region are much more modest. For the stars in the ring the increase in surface density is only a factor of a few. Density clumping on scales of 500 pcs to 1 Kpc are obtained around the rings and arcs formed in our simulations and these may correspond to the clumpiness observed in the gas/new star distribution in some ring galaxies.

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