COLLISIONAL RING GALAXIES

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1. Introduction

Ring galaxies are believed to represent a special case of a collision between two galaxies, in which one of the galaxies impacts and passes through the center of another disk system (e.g. Lynds & Toomre 1976). Although rare, this kind of low orbital–angular–momentum collision leads to a recognizable structure, namely a luminous blue star–forming ring (Appleton & Marston 1997), which should be easily identifiable even at moderate redshift. Indeed, Lavery et al. (1996) have used this fact, and their relative rarity at low-redshift, to conclude that rings (and therefore presumably all collisions) are over-represented in deep *HST* fields.

At low redshift, ring galaxies have been recognized as remarkable laboratories for the study of massive star formation (Fosbury & Hawarden 1977, Higdon 1995, Higdon & Wallin 1997; see also Appleton & Struck-Marcell 1996 for a recent review). In the collisional picture, the expanding near–circular density–wave, which is driven into the disk of the "target" galaxy by the gravitational perturbation of the "intruder", creates massive stars along the crest of the wave which should all have approximately the same age. If it can be shown that the massive stars are created almost simultaneously along the wave, then observed differences in the properties of the knots which make up the ring must be due to intrinsic variations in their properties. In addition, as the wave moves radially outwards, models predict that it should leave a trail of massive stars and star clusters in its wake (Appleton & Struck Marcell 1987a). The action of the wave may be to map stellar evolution radially across the face of the galaxy (see Marcum, Appleton, & Higdon 1992). Given an understanding of the basic dynamics of ring galaxies, they are a nice environment for testing stellar evolutionary models of some of the most massive star formation regions found in nature.

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2. Ring Galaxies as Laboratories for Studying Massive Star Formation

It was recognized early-on that the central perturbation caused by a head-on collision would drive density waves through the disk of a galaxy and that the subsequent star formation triggered by the passage of the wave might be a powerful test of star formation and stellar evolution in collisional systems (Appleton & Struck-Marcell 1987a, Struck-Marcell & Appleton 1987). Observations have confirmed many of the predictions of the earlier models in the sense that there is now compelling evidence that many ring galaxies do indeed owe there morphology to a propagating wave of star formation. Perhaps the most compelling evidence for this comes from thickness of the blue star forming ring in the Cartwheel ring galaxy (Borne et al. 1995, Struck et al. 1996). The ring at its narrowest is approximately 0.5-1kpc in width, which corresponds to a timescale of 8-16 million years if the ring is expanding at 60 km/s (Higdon 1996). The overall expansion time of the ring is at least 100 million year, and so the ring must represent the coherent triggering of massive O/B stars around the ring. From the careful modeling of the stellar evolution of knots in 10 ring galaxies, Bransford et al. (1997) has found a very similar story, in which the ages of most knots in ring galaxies are between 10 and 80 Myrs, and in all cases are significantly shorter than the ring expansion timescales derived from model-fitting the kinematics of the rings. These ground-based results also show that rings are mildly metal-poor and show little variation in metallicity from knot to know within a single galaxy.

In addition to the simultaneous triggering of the star birth in the wave, as it expands outwards, another prediction of the models seems to be consistent with observations, namely the expectation that stellar evolution will be mapped across the face of the galaxy as the wave expands. The idea here is that the youngest stars are born in the ring as it expands outwards compressing new ISM material. The models show that newly formed stars created in the wave are left behind by the wave, creating an age gradient in the radial direction. We would expect to find the oldest stars and star clusters in the inner regions of the galaxy, and the youngest stars would be found at the current position of the wave (the present position of the ring). Such a picture would naturally lead to radial color gradients and these are observed in many ring galaxies (Marcum, Appleton, & Higdon 1992, Appleton & Marston 1997). A radial distribution of dust could also cause a radial reddening–gradient and so mapping the dust in these galaxies is a priority (see below).

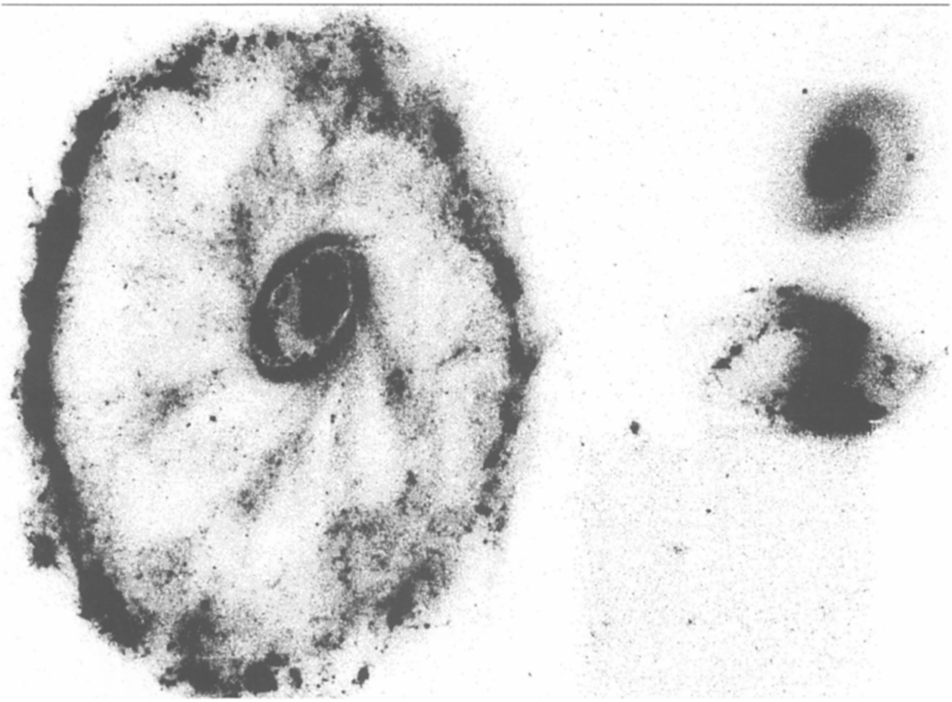

Figure 1. *HST* WFPC2 F450W Image of the Cartwheel Ring Galaxy.

3. *HST* Observations of the Cartwheel Ring Galaxy: Possible Formation of a Thick-disk Pre-Globular Cluster Population

Recent observations of the Cartwheel ring galaxy with *HST* (Borne et al. 1995, Struck et al. 1996, Appleton et al. 1997) have revealed a huge variety of structure in this classical ring galaxy, both in the outer and inner rings, and in the spokes between them. Fig. 1 shows a B-band *HST* image of the Cartwheel ring. The image show many star clusters and associations in the outer ring, as well as compact sources between the rings. The galaxy shows a dramatic difference in color between the massive star forming knots in the outer ring, and the inner regions of the galaxy. The range of color variation is from $-0.7 < B - I < 2.4$. In a recent analysis of the colors and luminosity of star clusters in the Cartwheel, Jacobs (1996), and Appleton et al. (1997) have concluded that the clusters found between the two rings are consistent with the colors and luminosity of a faded population of star clusters deposited about 100 million years ago, when we might have expected the expanding ring–wave to have passed through that region of the galaxy. These "inter-ring" knots are mainly unresolved at the resolution of the Wide-Field camera on WFPC2 (at an assumed distance of 120 Mpc for the Cartwheel, this corresponds to $\sim$ 50pc) and many are close to the completion limit of the observations ($B > 25.5$ mag). A number are also slightly resolved (at the 50 pc level) and may be regions of faint secondary star formation.

We are currently testing various hypothesis about the origin of the inter-ring clusters using survival analysis to investigate the shape of the luminosity function for these fainter clusters as they approach the limit. Preliminary results suggest that these clusters represent *faded remnants of the most luminous star clusters and associations seen in the outer ring* at the present time. Although these inter-ring clusters are still quite young (if the above hypothesis is correct), some of them may survive long into the future and may eventually become globular clusters with metallicities presumably in the range of those seen in other rings (1/2 to 1/5 solar in oxygen and nitrogen). Any metallicity gradient present in the original target disk would also be mimicked by the thick-disk population of aging clusters. It is interesting that a possible "thick-disk" globular clusters population has been seen in the Sombrero galaxy (= NGC 4594) (Forbes, Grillmar, & Smith 1997). Perhaps near-central collisions between gas-rich progenitors might be one mechanism for creating such a population.

4. Molecules and Dust in Ring Galaxies

The recent discovery by Gao et al. (1997), that the ring galaxy Arp 118 (NGC 1144) is extremely bright in the ^{12}CO line (it is twice as bright in the CO line as Arp 220) suggests that violent collisions are capable of converting significant amounts of neutral hydrogen into molecules. In a conventional galaxy interaction or merger, it is believed that gas is funneled into the center of the galaxies by the action of tides. However, when two disks collide head-on, it is not obvious what causes an enhancement in the ratio of H_2 to HI, and yet such an enhancement is observed (Horellou et al. 1995). We have recently obtained HI observations of Arp 118 with the VLA, and have discovered rather weak HI emission, but very strong absorption lines against two sources of radio emission in NGC 1144. The thesis observations of C. McCain (with K. Freeman at Stromlo-private communication) suggests a collision between two gas rich disks in which large-scale shocks are present. Understanding the mechanisms that can convert large amounts of neutral hydrogen into molecules in this process will be a major challenge of models of the hydrodynamics. The recent models of Struck (1997) attempt to investigate the different thermal phases of the ISM during such violent collisions, and such work is producing interesting results, including the formation of new gas disks around the companion.

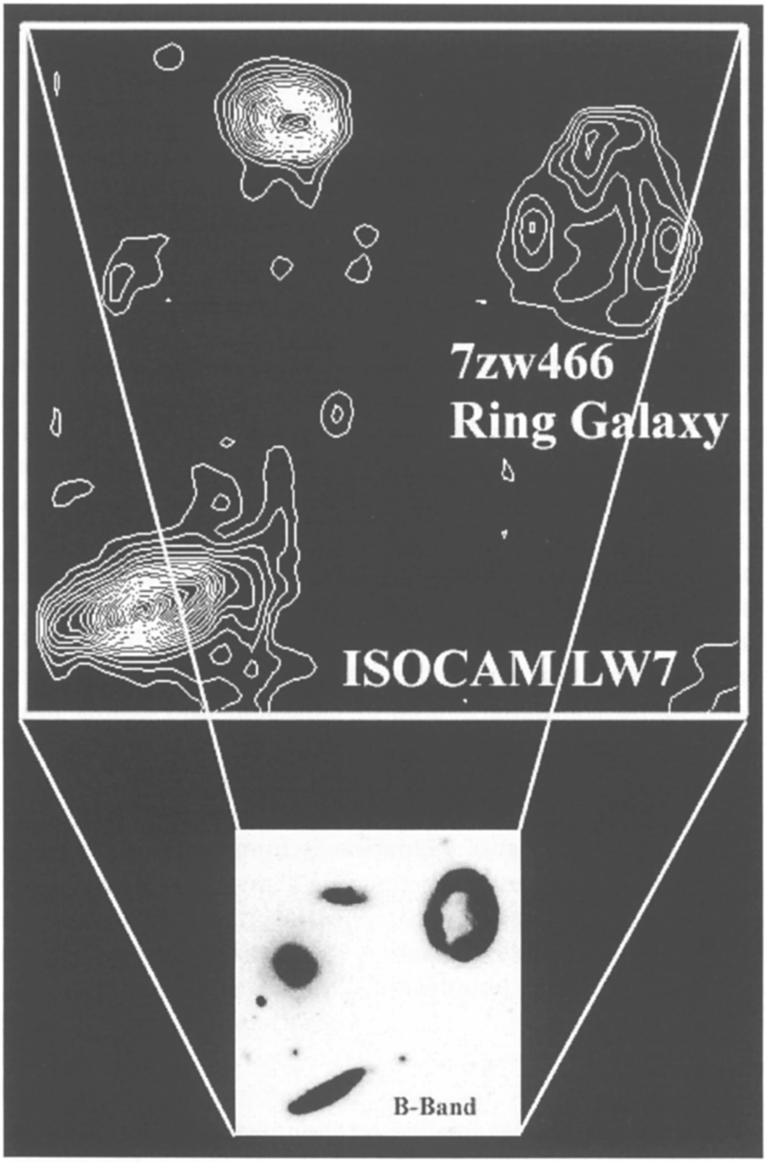

Figure 2. *ISO* $\lambda 12\mu$m contour map of the VII Zw 466 Group (Optical Inset). Note that the elliptical galaxy is not detected. The brightest emission is from the northern background galaxy and the edge-on disk.

It has been know for some time that ring galaxies emit about half of their bolometric luminosity in the Far-IR (Appleton & Struck 1987, Wakamatsu & Nishida 1988). Until recently little was known about the distribution of

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dust in ring galaxies. For example, optical spectra of VI Zw 466 (Bransford et al. 1997) show that the Balmer decrement in this galaxy (usually taken as a indication of the optical extinction) is quite similar from one knot to the next around the ring, suggesting uniform extinction. However *ISO* observations (see Fig. 2) by Appleton et al. (1997) reveal a major asymmetry in the dust emission at Mid-IR wavelengths, showing strong emission along the north-western quadrant of the ring where the λ3cm radio continuum emission is also stronger. The *ISO* emission pinpoints the regions of warm dust in the galaxy, perhaps indicating regions where young stars are more dust-enshrouded.

The Cartwheel at *ISO* wavelengths (Charmandaris et al. 1997) shows a rather different picture. At $\lambda 15\mu$m, where thermal emission from warm dust dominates, only one small intensely powerful cluster of HII regions of the ring (the region called Knot A by Higdon 1995) is detected. This seems surprising because much of the southern quadrant of the Cartwheel's outer ring shows very powerful Hα emission (Higdon 1995). Could the HII regions in the Cartwheel be creating small fountains which have lifted the grains to a larger scale-height that in VIIZw466? The lower metallicity of the Cartwheel's outer ring may also be a factor, although oddly most of the star–forming outer ring is detected by *ISO* at $\lambda 7\mu$m, where PAHs are believed to be the main source of emission, and grains have clearly been formed. Another interesting result from the *ISO* observations of the Cartwheel is the detection of strong $\lambda 15\mu$m emission from the center of the galaxy (Charmandaris et al.) in the regions of the second ring and nucleus. Since little or no signs of star formation is found at optical wavelengths, the source of the central emission remains a mystery. It may originate in a dust-enshrouded starburst, in grains heated by infalling gas from the HI plume (see Struck et al. 1996) or from a stronger than normal UV radiation field from a post starburst population.

5. Conclusions

Recent work on ring galaxies has led to the following conclusions:

a) ring galaxies have sub-solar metallicities in the range 1/2 to 1/5 solar in [O/H] and [N/H] ratios (Bransford, Appleton, & Marston 1997). There is a suggestion of an increase in the mean nitrogen abundance for rings of larger linear size, but the oxygen abundances show no trend with ring diameter. The increase in nitrogen abundance with ring diameter probably reflects the original nitrogen abundance of the target galaxy before the collision. There is no clear decrease in metallicity with ring diameter, as might be expected if the rings travel down metallicity gradients present in the target galaxy. (A glaring exception is the Cartwheel which has a very metal-poor outer ring (Fosbury & Hawarden 1977).)

b) the colors of the knots in ring galaxies (after correcting for the effects of reddening) are consistent with very young star formation regions with typical ages in the range 20-80 Myrs (see BAM). These ages are significantly shorter than the expansion ages of the rings of 200-300 million years, providing strong evidence that the star formation in the ring waves are created by a single coherent event, the expanding wave, which triggers star formation through compression of the disk.

c) by a comparison with models of starburst populations it is possible to show that most ring knots are totally dominated by the young stellar population, and show only a small contribution from the underlying stellar density wave. Although Lynds & Toomre (1976) were probably correct in their suggestion that the rings are produced by a crowding of disk material due to the collisional perturbation, the rings are defined more by the *gas response and young stellar population, than by the underlying old population.*

d) *HST* observations of the Cartwheel ring (Borne et al. 1996, Struck et al. 1996, Jacobs 1997, Appleton et al. 1997) show that the ring is resolved into hundreds of star forming regions which show a large scatter in color consistent with clusters of young stars 10-20 million years old. The smoothed-out light distribution is consistent with a radial expanding starburst population superimposed on a $1/r^2$ disk of red light. Approximately 50 star clusters are seen between the inner and outer rings in the Cartwheel, and these clusters have the colors and magnitudes consistent with faded versions of the brightest clusters seen currently in the outer ring. This can be taken as evidence that the outer starburst ring has expanded to its present size by moving through the inner disk and depositing star clusters in its wake. We note that some of the star clusters seen between the rings may also be regions of faint secondary star formation formed in the "spokes" which connect the inner to outer rings. New narrow-band imaging of the Cartwheel by J. Higdon (ATNF) may help to shed light on this topic.

e) The star clusters seen between the inner and outer rings of the Cartwheel have absolute magnitudes on the range -13 to -10 and $B-I$ colors of 0.8-1.2 mag. (assuming D = 120 Mpc). If they are evolving star clusters formed by the radial passage of the density wave, then they may hint at a way of forming a thick disk population of globular clusters. Such star clusters, if they could survive for another few 10^9 yrs, would have the luminosity and colors of globular clusters, although they would mimic any metallicity gradient present in the original galaxy. Collisions of this kind (which drive radial expanding waves) may help to explain the possible thick-disk globular clusters seen in galaxies like the Sombrero galaxy.

f) *ISO* observations of two ring galaxies (Cartwheel—Charmandaris et al.

1997, VIIZw466—Appleton et al. 1997) show emission from PAHs, and probably larger grains in thermal equilibrium with the radiation field from the young stars. In the Cartwheel, the shorter-wavelength (PAH) emission follows the distribution of young stars better than the longer-wavelength (thermal) IR, suggesting that the smaller PAH grains are more sensitive to the uv field than the larger grains.
g) The *ISO* observations of the inner regions of the Cartwheel reveal a relatively powerful $15\mu m$ source which seems coincident with the inner ring and bulge (Charmandaris et al. 1997). Since only very weak HII regions are seen from this regions we speculate that the emission comes from either an obscured starburst, grains heated by infalling material from a tidal stream, or grains heated by a post-starburst population.

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