RevMexAA (Serie de Conferencias), **6**, 141–144 (1997)

COLLISION-INDUCED STAR FORMATION IN RING GALAXIES

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RESUMEN

Presentamos imágenes en B e I de la galaxia "Cartwheel" y sus dos galaxias vecinas, obtenidas con el WFPC2 del *HST*. Ellas muestran la *formación estelar en la onda de choque con forma de anillo en expansión*, en los "rayos", en el núcleo de la galaxia y en las dos galaxias vecinas. Se observan detalles hasta el límite de resolución y *se encuentran objetos muy jóvenes y compactos (quizás cúmulos jóvenes y masivos) en las regiones de formación estelar*. El anillo principal está lleno de *arcos, filamentos, burbujas y regiones azules de formación estelar*, todos bien resueltos en nuestras imágenes. Los "rayos" del anillo primario son claramente visibles aunque más difusos que los del anillo exterior, indicando que la onda de choque se ha debilitado y que las asociaciones estelares de los "rayos" se dispersan a medida que envejecen.

ABSTRACT

We present results from *HST* WFPC2 B- and I-band imaging observations of the "Cartwheel" ring galaxy and its two nearest companions. The combination of images has been used to study and to characterize the *intense star formation activity in and around the expanding ring density wave*, in the Cartwheel's "spokes" region, in the nucleus of the galaxy, and in the two companions. Fine structure is observed down to the resolution limit of the *HST* images and *very young compact objects (perhaps massive young clusters) are found throughout the star-forming regions*. The primary ring around the galaxy is full of *loops, filaments, bubbles, and blue star-forming knots*, which are well resolved in our images. The "spokes" of the Cartwheel, which are interior to the primary ring, are clearly visible, though their structure is somewhat more amorphous than that of the outer ring, suggesting that indeed the massive star formation behind the expanding density wave has subsided and the stellar associations that comprise the spokes are dispersing as they age.

Key words: **GALAXIES: INDIVIDUAL: CARTWHEEL — GALAXIES: INTERACTIONS — GALAXIES: STARBURST — STARS: FORMATION**

1. AN INTERACTION-INDUCED STARBURST: THE CARTWHEEL RING GALAXY

We have obtained high-resolution B and I imaging with the *HST* of the "Cartwheel" ring galaxy, as an example of interaction-induced starburst activity (Borne et al. 1996a,b; Struck, Appleton, Borne, & Lucas 1996). The "Cartwheel" is number AM0035-335 in the Arp & Madore (1987) catalog of southern peculiar galaxies. Of the many types of interacting and merging galaxies known, the rare and beautiful smoke-ring galaxies are among the most straightforward to interpret dynamically. Since the pioneering models of Lynds & Toomre (1976) and Theys & Spiegel (1977) it has become accepted that many "classical" ring galaxies are formed from a head-on collision between a small intruder galaxy and a larger disk system. The ring forms, as gas and stars, are crowded into an expanding wave that moves radially through the disk. The passage of the wave triggers vigorous star formation in the rings and provides us with a remarkably simple example of density wave-induced star formation (Struck-Marcell 1990; Gerber 1993; Struck-Marcell & Higdon 1993; Gerber & Lamb 1994; Mihos & Hernquist 1994). Recent ground-based observations of rings (Marcum, Appleton, & Higdon 1992; Marston & Appleton 1995; Higdon 1995) reveal stellar evolutionary effects in and behind the expanding rings that strongly support the collisional picture. The Cartwheel ring galaxy presents unusually strong density wave-induced

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starburst activity in the wake of the collision event that formed the ring. Unlike many regions of massive star formation, the site of the youngest (most massive) stars in rings is continually expanding, leaving behind in its wake a trail of evolving stars. The high spatial resolution of the *Hubble Space Telescope (HST)* provides an exciting opportunity to investigate the properties of massive OB associations formed in this expanding wave and provides a glimpse into the formation sequence of the most massive stars found in nature. The most dramatic changes are likely to occur on the leading edge of the expanding wave where the most massive stars will be found. These H II regions are dominated by stars with $M > 10$ $M_{\odot}$, whose lifetimes are typically less than a few times 10^7 years. If such stars were born on the edge of a typical ring expanding at 100 km s^{-1} into the surrounding disk, then the extremely massive O stars would exist in a band only 0.3 kpc wide. At the typical distance of a ring galaxy (100 Mpc) this corresponds to $\sim 0.6''$.

2. GENERAL PROPERTIES OF THE CARTWHEEL SYSTEM

We have combined the B and I band images to form an approximately true-color image of the Cartwheel system. The full-color rendition of the *HST* Cartwheel observations has been widely distributed (e.g., see the press release version of the image at the STScI Public Outreach WWW site). Figure 1 (Plate 3) reveals a complex pattern of sharp color variations in and around the Cartwheel, with the bluest colors found in the outer ring and the reddest colors found in the inner regions. However, this figure does no justice to the wealth of fine-scale detail revealed in the original images. There is a well defined secondary ring around the nucleus and a lens (or disk) interior to that. This region is heavily reddened and clearly full of dust. The images reveal a *very fine structure in the dust distribution* around and interior to the secondary ring. A nearly point-like nucleus is seen within the inner disk. In comparing the images from the two pass-bands, we find that there is a significantly smoother component to the light in the I band than in the B band. For example, the core region and the inner ring reveal point sources and a more patchy luminosity distribution in the B band. The original full-color image shows that the outer ring is also clearly dotted with a number of extraordinarily blue point sources. Surprisingly, the spokes interior to the outer ring (though somewhat blue) remain amorphous even at high resolution, probably indicative of older expanding stellar associations comprising the spokes. The two nearby companions also reveal distinctive properties. The western-most companion is irregular and non-nucleated, though similar to a small barred spiral, and it contains a collection of intensely blue point sources. The eastern-most companion appears to be an S0 galaxy, is predominantly red in color and much smoother in appearance, and has a faint (tidal?) tail (apparently stellar) extending to the east. Our images portray a remarkable richness of information about the Cartwheel system. Its stunning contrasts are also quite evident: the redness of the S0 companion compared to the very blue Irr (SB?) companion, the red core and red inner ring of the Cartwheel compared to the considerably bluer outer ring. The star formation on the south side of the outer ring is demonstrably more intense than that on the north side. The spokes are indeed comprised of young stellar populations, though not as intensely blue (i.e., young) as the outer ring. The core also reveals a complex structure not discernible from the ground-based images: dust lanes cutting across and passing around the inner ring, a lens-like "bulge" region interior to the inner ring, and a sharp nucleus.

3. STRUCTURE OF THE RING, SPOKES, AND CORE REGIONS

The Cartwheel ring annulus is nearly $5''$ across, thereby comprising many WFPC2 resolution elements across the ring. The ring demonstrates a wealth of sharp features: star-forming knots, stellar clusters, arclets, bubble-like regions, and holes in the ring (blast regions?). The arclets, bubbles, holes may be similar to the vast multi-supernova-driven arc reported by Vader & Chaboyer (1995) for NGC 1620. The spoke region of the Cartwheel is surprisingly amorphous. This would not have been obvious initially from the ground-based images, which showed a complex knotty structure both in the outer ring and in the spokes. The diffuseness of the spoke region is likely a result of the aging and diffusion process for the expanding stellar associations that lie in this region —in the wake of the expanding ring density wave. Numerous circular regions (bubbles?) and young stellar clusters are seen among the spokes, both probably indicative of the earlier violent star formation history within this region. The *HST* images reveal a significant level of detail in the core of the Cartwheel. There is a clear lens-like core interior to the inner ring, a sharp nucleus within the core, some bluish clusters around the inner ring, a complex pattern of small-scale dust features, and a three-dimensional appearance (with the spokes continuing across, behind, and into the inner ring). The inner ring is likely illuminated by older stars (from the collision-induced starburst) now ascending the giant branch.

4. DUST, GAS, AND STELLAR POPULATIONS

The *HST* images of the inner regions of the Cartwheel reveal many fine-scale dust features in and around the core. Marcum, Appleton, & Higdon (1992) found very little evidence for a pre-existing stellar population outside the core. The redness of the central region is thus likely a combination of the older stellar population and the significant dust component embedded therein. They also found that most of the HI is concentrated in the outer ring, which is the bluest (and hence most intensely star-forming) region of the galaxy. Unlike the core region, there is probably very little contamination of the young stellar populations in the outer ring and spoke regions with an older population.

5. COLOR GRADIENTS, 3-D STRUCTURE, AND YOUNG CLUSTERS IN THE CARTWHEEL

One of the goals of the *HST* observations that has been spectacularly fulfilled has been the detection of color gradients in the ring. Gradients are seen around the ring (bluest on the south side) and across the ring, where there is a different sense to the color gradients on opposite sides of ring. The most intense star formation is on the south side of the outer ring, which is sharper, bluer, and shows more young stellar associations (young globular clusters?). On the south side, the color gradient across the ring is such that the outer part of the ring is bluest; the opposite is seen on the north side of the ring. This peculiar change in the color gradient from south to north has in fact been seen in numerical models by Mihos (private communication) —the result is due to the *three-dimensional warping of the ring plane*, thereby projecting the "physically outermost" (and hence bluest, most intense star-forming) region interior to the "projected outermost" region on the north side, and vice versa on the south side. If this interpretation is correct, then the observed color variations are evidence for the expected three-dimensional character of this very disturbed collision remnant. Many authors have now reported the detection of young globular clusters in *HST* images of merging galaxies. These clusters are apparently forming in the shocked gas components of the constituent gas-rich galaxies involved in the collisions. For a discussion of these observations and their interpretation, refer to Holtzman et al. (1992), Whitmore et al. (1993, 1995), Shaya et al. (1994), Conti & Vacca (1994), Zepf et al. (1995; and references therein), Whitmore & Schweizer (1995), and Ho (this volume). We believe that we are seeing a very rich population of similar objects throughout the outer Cartwheel ring.

The *HST* imaging observations of the Cartwheel ring present a wealth of sharp features: star-forming knots, stellar clusters, arclets, bubble-like regions, and holes in the ring (blast regions?). The knots and clusters (young globular clusters?) appear similar to those that many authors have now reported in *HST* images of other interacting and merged galaxies. We believe that all of these features are direct indicators of intense interaction-induced starburst activity in this galaxy.

This research was supported in part by NASA *HST* grant GO–05410.01–93 from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS5–26555.

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