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Massive Star Formation and Dust in Collisional Ring Galaxies: From *GALEX* to *Spitzer*

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Abstract. We present some first results from a *GALEX* and *Spitzer* survey of a dozen collisional ring galaxies. The combination of UV and mid-IR imaging and spectroscopy will allow us to investigate the relationship between massive star formation sites, PAH molecular–band strengths, and dust heating in these mainly simultaneous starburst rings. A deep observation of the well-known Cartwheel ring galaxy has revealed a gigantic outer UV disk which extends to at least twice the radius of the outer blue star–forming ring. A lack of UV variability in the outer Cartwheel ring rules out an intermediate-mass black hole (IMBH) as the origin of the brightest of a dozen ULX source seen by *Chandra* in the ring.

1. Introduction

Two out of three of the most UV-luminous galaxies in the local universe are collisional ring galaxies–formed when a disturbance is driven out through a galaxy disk as a smaller galaxy plunges through the center of the larger system (Toomre 1978, Appleton & Struck 1996 for review). The resulting density wave can trigger an almost simultaneous burst of star formation around the ring which propagates outwards into the surrounding disk where low metallicity and minimal obscuration contribute to a high UV luminosity. The star forming rings contain very young powerful star clusters, warm dust and, in the case of the Cartwheel, large numbers of ultraluminous (ULX) compact X-ray sources (Gao et al. 2003). The aftermath of the expanding ring-wave, in the interior of

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the ring, can be the site of interesting ISM cloud physics. Gas clouds, having been strongly disturbed by the wave passage, can sometimes reform creating a lower level of fragmentary star formation. Self-gravitating disk models show that spokes can be produced in the disk behind the wave as gas accumulates and is sheared by the disk motion (Hernquist & Weil 1993, Struck-Marcell & Higdon 1993). Additionally, ring galaxies may have cosmological significance, since more rings are found in deep HST images than expected from modest merger rate extrapolations to high redshift (Lavery et al. 2004), perhaps indicative of a larger number of high-z head-on collisions.

2. Observations

We are conducting a *GALEX* UV, and *Spitzer* mid-IR imaging and IRS spectroscopy program of 12 collisional ring galaxies to investigate UV and X-ray heating sources in rings and ring interiors, and their influence on dust and molecular emission. We aim to explore the relative strength and power emitted in mid-IR PAH bands as a function of UV/X-ray continuum flux and galaxy structure. We will also attempt to calibrate the UV and IR properties of ring galaxies for future higher redshift studies where these luminous UV galaxies will appear redshifted into optical bands. We have also drawn from the growing *Spitzer* public archive (e. g. IRAC images of LT41 and the Cartwheel). Additional spectroscopy and imaging for Arp 143 is provided in collaboration with B. Brandl (Leiden) and W. Reach (SSC).

2.1. The Cartwheel and Discovery of Extended UV Disk

Early in the GALEX GI1 cycle, we obtained deep (4.5ks) UV data for the Cartwheel. We show in Fig. 1 (left panel) a multi-wavelength view of the Cartwheel ring galaxy obtained from Chandra (X-rays: Gao et al. 2002), HST (Visible: Struck et al 2003), GALEX (UV: this work) and *Spitzer* (IR: Public archive, Higdon et al. in prep.). The figure shows the dramatic change that occurs as one moves to longer wavelengths. At short X-ray and UV wavelengths, the predominant sources of energy are in the young outer ring where high-mass star formation and X-ray binary evolution occur rapidly and are confined to a narrow annulus. Notice the almost featureless sea of UV radiation from the ring interior with the faint superposition of spokes. At longer optical and IR wavelengths, the interior of the ring emerges. The low–level, dust–obscured star formation in the ring interior was first seen in ISO data by Charmandaris et al. (1999).

Secondary star formation, as indicated by both the smooth interior UV emission and the faint IR/optical spokes, shows that the aftermath of the outwardly propagating wave has modified (and perhaps suppressed) the ISM's ability to create significant new star formation. This may be an example of ISM feedback with a suppression timescale equal to the ring propagation time: approximately 100 Myrs.

Fig. 1 also shows the radial profile of UV light and color of the galaxy. Note the discovery of a highly extended UV disk extending to at least twice the radial dimensions of the outer Cartwheel ring. This low–surface–brightness exponentially declining disk follows closely the radial profile of another galaxy, NGC 772 (solid lines), which also has a huge UV extent. The outer Cartwheel disk is the first evidence that the Cartwheel progenitor galaxy was over 80 kpc in diameter. It is not yet known why this disk contains UV emitting stars which must be relatively young to emit in the Far-UV: this part of the disk should be unperturbed by the collision of the intruder. Work is continuing to search for counterparts at other wavelengths.

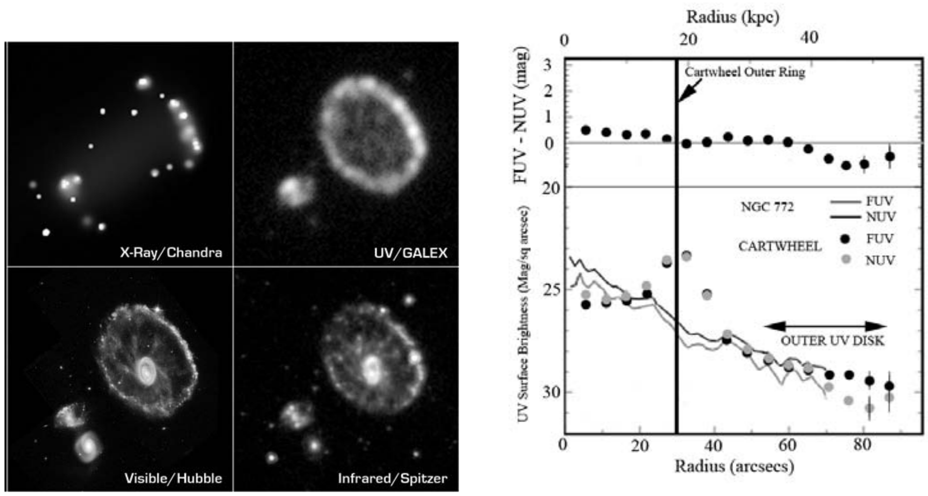

Figure 1. Left panel: Cartwheel Ring Galaxy from the X-rays to the IR. Right panel: Radial surface brightness and color profiles from the Cartwheel ring center. Filled dots represent the FUV and NUV points and the solid line shows the surface brightness of NGC 772.

2.2. IRS Spectroscopy

Fig. 2 Left panel: shows a multi-wavelength view of Arp 143, a collisional ring galaxy in the early stage of ring formation (see Appleton, Schombert & Robson 1992). As with the Cartwheel, the center of the galaxy is less UV bright. Faint spokes are seen in the *Spitzer* 8μm image, again suggesting a build-up of lower level star formation activity after the main wave has passed through that region of the disk. One particular knot of IR emission is almost invisible optically, but is quite prominent in the IR. Spectroscopy, like that in Fig. 2 (Right panel) is helping us interpret the *Spitzer* images.

3. Conclusions

We are still in the data collection stage for the *Spitzer* part of the project and in an early stage in the analysis of these *GALEX* data. This paper is a progress report showing early imaging results and preliminary spectroscopy. *Spitzer* IRS spectroscopy has been obtained or will soon be scheduled for LT41, NGC 985, Arp 10, Arp 148 and Arp 147.

Preliminary results from the *GALEX* study of the Cartwheel ring (Appleton et al. in prep.) from two epochs indicate that none one of the bright outer ring knots show significant time variability over a 1 year interval. This fact, in

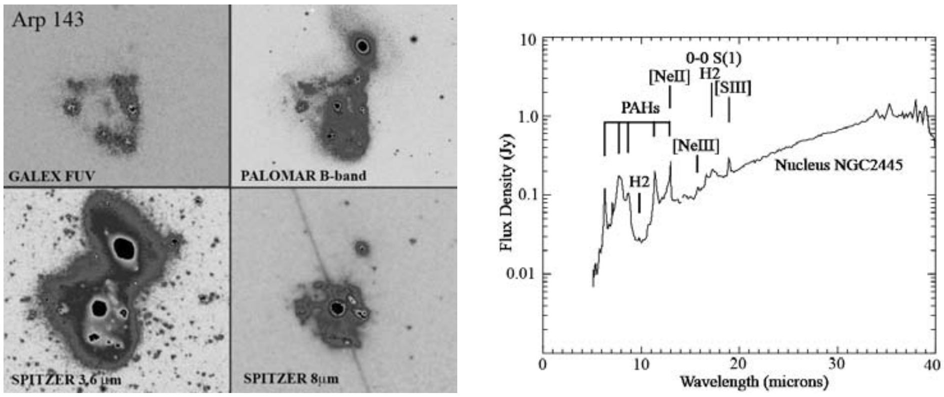

Figure 2. Left panel: Arp 143 from GALEX to *Spitzer*. Right panel: IRS combined short-low and long-low spectroscopy of the nucleus of NGC 2445 (lower left of the pair in the left panel).

association with a measurement of the X-ray to UV spectral index, suggests none of the ULX/HLX sources are single accretion-driven sources. It is much more likely that the X-ray sources are collections of high mass X-ray binaries loosely associated with massive, luminous UV/optical star clusters. FUV/NUV color variations around the outer ring show a relatively small range of color differences and variations are being correlated with absorption by dust grains, as mapped by *Spitzer*. Larger FUV/NUV color variations are seen in the inner parts of the Cartwheel where stronger Mid-IR emission is seen, which is an indication of the relatively increased importance of obscured star formation in the inner disk.

The discovery of a gigantic exponentially declining UV disk extending to at least twice the size of the outer Cartwheel ring provides, for the first time, a glimpse of the nature of the pre-collisional "target" galaxy in the Cartwheel. However, it remains a mystery as to why this disk contains a relatively young (B-star or younger) stellar population. One speculation is that the outer ring of the Cartwheel is the second, not the first, ring wave to propagate out through the galaxy. In such a picture, the first wave would have already propagated off the disk but left behind a disturbed ISM.

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