MID-IR IMAGING OF COLLISIONAL RING GALAXIES WITH ISOCAM*

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ABSTRACT

We present mid-IR images and spectra of three collisional ring galaxies observed as part of the ISO GT program CAMACTIV (P.I. I.F. Mirabel) by ISOCAM. The observations, reveal the distribution of hot dust in the galaxies and enable us to probe the mechanisms responsible for the heating of the ISM. Even though the mid-IR colors of Arp 10 were typical of those found in spiral arms of late type spirals, the Cartwheel (AM 0035-33) galaxy revealed a surprisingly strong mid-IR emission from the nucleus which we attribute to a previously undetected star formation activity. The third ring of the sample, Arp 118, harbours a Seyfert 2 nucleus which exhibits a clearly detected hot continuum in the [5.1-6.7]μm range.

Key words: interacting galaxies; starburst; mid-infrared astronomy

1. INTRODUCTION

Collisional ring galaxies, of which the Cartwheel is the "prototypical" candidate, are believed to form when an "intruder" galaxy passes through the center of a rotating disk of a larger "target" galaxy (Lynds & Toomre 1976; Theys & Spiegel 1976; Appleton & Struck-Marcell 1996 and references therein). The perturbation triggers a radially expanding ring-like density wave on the disk, causing massive star formation in the ring (see Appleton & Marston 1997). The symmetry and well defined dynamical history of ring galaxies has made them ideal candidates for studies of the phase transition of the interstellar medium due to collisionally induced star formation.

2. OBSERVATIONS

The Cartwheel group was observed with ISOCAM in a 2×2 raster mode using two broad band filters centered at 6.75μm (LW2), and 15μm (LW3) and a 6 arcsec pixel field of view. The mid-IR maps cover the Cartwheel galaxy and the two nearby companions G1 and G2. Arp 10 was observed in a similar configuration using though a 3 arcsec PFOV. On the other hand, Arp 118 was sufficiently bright in the mid-IR so that we could obtain a full mid-IR spectrum of a 96 ×96 arcsec region centered on the galaxy using the circular variable filter (CVF) and a 3 arcsec PFOV.

The standard data reduction procedures described in the ISOCAM[1] manual were followed. Dark subtraction was performed using a model of the secular evolution of ISOCAM's dark current. Cosmic rays were removed using a multi-resolution median filtering method while the memory effects of the detector were corrected using the so-called IAS transient correction algorithm which is based on an inversion method. The final raster was constructed after using the instrumental flat fields and correcting for the lens field distortion. These methods and their consequences are discussed in detail in Starck et al. (1998).

3. THE SAMPLE

3.1. Arp 10

Arp 10 (= VV 362) is a collisional ring galaxy (distance = 122 Mpc) containing a bright ring, an off-center nucleus and a faint bar. Deep Hα images by Charmandaris et al. (1993) revealed, in addition to the bright outer ring, a very small inner ring and traces of outer ring arcs. A study of its atomic hydrogen content (see Charmandaris & Appleton 1996 and references therein) suggests that the HI disk consists of two main parts: a very irregular outer structure, and a more regular inner disk associated with the main bright optical ring. Evidence for optical shells or ripples in the outer isophotes of the galaxy reminiscent of the ripples seen in some early type systems are present.

Our ISOCAM images (see Fig. 1) clearly show that the mid-IR emission is associated with the bright

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outer star forming ring and the nucleus. Due to our limited resolution, the small inner ring could not be discriminated from the nucleus and the mid-IR counterparts of the star formation threshold effects discovered by Charmandaris *et al.* 1993 could be put in stringent tests. The mid-IR flux from the nucleus (18 mJy in the LW2 filter and 20 mJy in the LW3 filter) represents almost 65% of the total flux in both filters. This is in agreement with the star formation activity on the galaxy since most of the Hα flux originates from the inner ring and nucleus (Charmandaris *et al.* 1993). The mid-IR color ratio LW3/LW2$\sim$1.1, a value typical in star forming regions of late type galaxies, almost everywhere in Arp 10.

3.2. The Cartwheel

The Cartwheel galaxy was discovered by Zwicky at a distance of 121 Mpc (H$_o$=75 km s^{-1} Mpc^{-1}). It has a bright outer ring and an inner ring which is connected to the outer one with a series of "spokes" (see Fig. 1 in Higdon 1996). Three small companion galaxies located north and north-east of the ring complete the group. It is still unclear which of the companions is the culprit for the creation of the Cartwheel ring, but it is likely that each of them contains sufficient mass to trigger the generation of the star forming ring (see discussion by Appleton & Struck-Marcell 1996). On-going efforts to simulate the dynamics of the system have been focused on the nearby companion G2 (Bosma priv. comm.) and on the most distant one, G3, (Horellou priv. comm.) which seems to be connected to the Cartwheel with a plume of HI gas (Higdon 1996).

Our ISOCAM observations reveal that one-third of the circumference of Cartwheel's outer ring is detected in the LW2 band (see Fig. 2a). The detected segment of the ring corresponds to the brightest part of the optical ring as defined in the Hα. About 1.4 mJy (60% of the LW2 flux from the outer ring) comes from a hot-spot in the ring, unresolved to our observations, which corresponds to the position of two large HII region complexes.

Interestingly, in the LW3 filter, only the hot-spot is detected (at 7.5 mJy) in the outer ring (Fig. 2b), and the only other emission from the Cartwheel is from the central regions (3.8 mJy in LW3 and 3.6 mJy in LW2). The LW3/LW2 flux ratio, often used as a diagnostic of the intensity of the radiation field, of the hot-spot is 5.2, a value which is among the highest detected in all interacting galaxies of the CAMACTIV sample. For comparison, the highest LW3/LW2 flux ratio detected in the interacting galaxy NGC 4038/39 is only 2.6 and it is found in the region where the two disks overlap (Mirabel *et al.* 1998).

A clue as to why the hot-spot is different comes from a comparison with radio and optical observations (Higdon 1996). The hot-spot coincides with the peak of the 20 cm and 6 cm radio continuum emission from the ring, and, unlike the rest of the outer ring, shows a sudden drop in HI surface density at that point. Assuming that the HI absorption is not responsible for the drop in surface density, this suggests that most of the cool gas in the hot-spot region is either ionized and/or has already been converted into stars. The very powerful UV radiation field in the hot-spot implied by its radio and Hα emission – the Hα surface density is at least a factor of 3 times higher there compared with the other regions of the ring – would be expected to illuminate a *larger volume* of interstellar grains, thereby boosting the thermal continuum at longer wavelengths sampled by the LW3 filter relative to the shorter wavelength PAH-dominated LW2 emission. For an ideal spherical HII region of radius R, its volume is proportional to R^3 while the volume of the associated photo-dissociation-region (PDR) which has a shell shape would vary as R^2. Hence, the filling factor of the HII regions in a given giant molecular cloud of the ISM would increase with a higher rate than the corresponding PDRs. Moreover, in a strong UV environment, the dissociation of PAH molecules would further diminish their contribution to the LW2 flux.

Although centrally concentrated, the emission from the central regions is resolved and a faint filament of LW2 emission extending to the west of the nucleus follows one of the "spokes" seen in optical images. However, it was initially a surprise for us to detect such a strong signal from the center of the Cartwheel, which had previously been believed to be almost devoid of nuclear activity (Fosbury & Hawarden 1977; Higdon 1995). The center of the Cartwheel exceeds the outer star-forming ring by a factor of 1.6 in LW2 while it has 0.4 times the flux of the outer ring in LW3. The nuclear region has mid-IR colours similar to those of late type galaxies (LW3/LW2 = 1.1), although optically, it has very red colours suggestive of an older stellar population (Struck *et al.* 1996). As a result of this discovery, follow up CO observations revealed the presence of 1.5×10^9 M$_\odot$ of H_2 in the nuclear regions in agreement with the collisional scenarios (Horellou *et al.* 1998).

The morphological types of the two nearby companions of the Cartwheel are distinctly different. The eastern companion (G2) is an early type S0 galaxy. This explains the contrast on the LW2 over LW3 emission from the two companion galaxies since in early type galaxies the mid-IR emission is dominated by the old stellar population. The LW2 flux is typically 6 times stronger than the LW3 emission which is consistent with temperatures of $\sim$5000 K. Since the LW2 emission of G2 is just $\sim$4 times stronger than the rms noise of the LW3 emission any expected stellar contribution to the LW3 filter measurement would be below our detection limit. The ratio of LW3 to LW2 flux of G1 is $\sim$1.4, a value found in most normal late type galaxies (see Charmandaris et al. 1999 for more details).

3.3. Arp 118

Arp 118 is one of the three collisional rings which host an identified Seyfert nucleus. Its IR luminosity is L$_{IR}$=2.5×10^{11} L$_\odot$, almost 10 times higher than other ring galaxies. Moreover, a recent study of its molecular gas (Gao *et al.* 1995) revealed an extremely disturbed system with the nucleus being displaced off-center suggesting that the elliptical companion which led to the ring formation is a considerable fraction of its mass. The CO luminosity is twice that of Arp 220 and its velocity width (650 km s^{-1}) is 2-3 times higher than most ring galaxies.

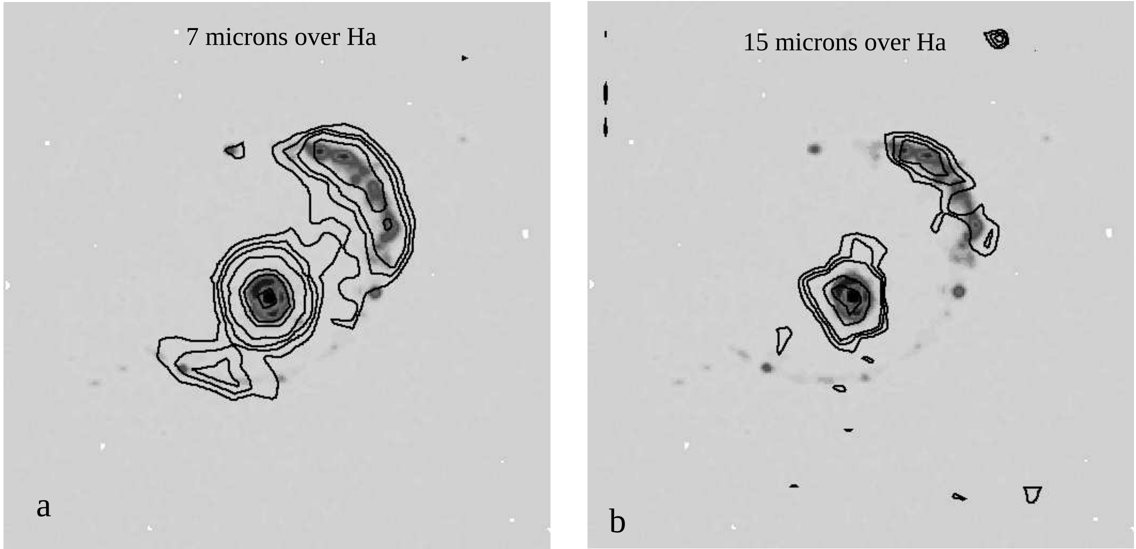

Figure 1. *Arp 10: a) Contour map of the ISOCAM LW2 emission overlayed on an Hα image (Fig. 3 of Charmandaris et al 1993). The contour levels are 0.2, 0.25, 0.3, 0.4, 0.8, 1 and 1.5 mJy/pixel. b) Contour map of the ISOCAM LW3 emission overlayed on the same Hα image. The contour levels are 0.3, 0.4, 0.5, 1 and 1.5 mJy/pixel. North is up and East is left in both images.*

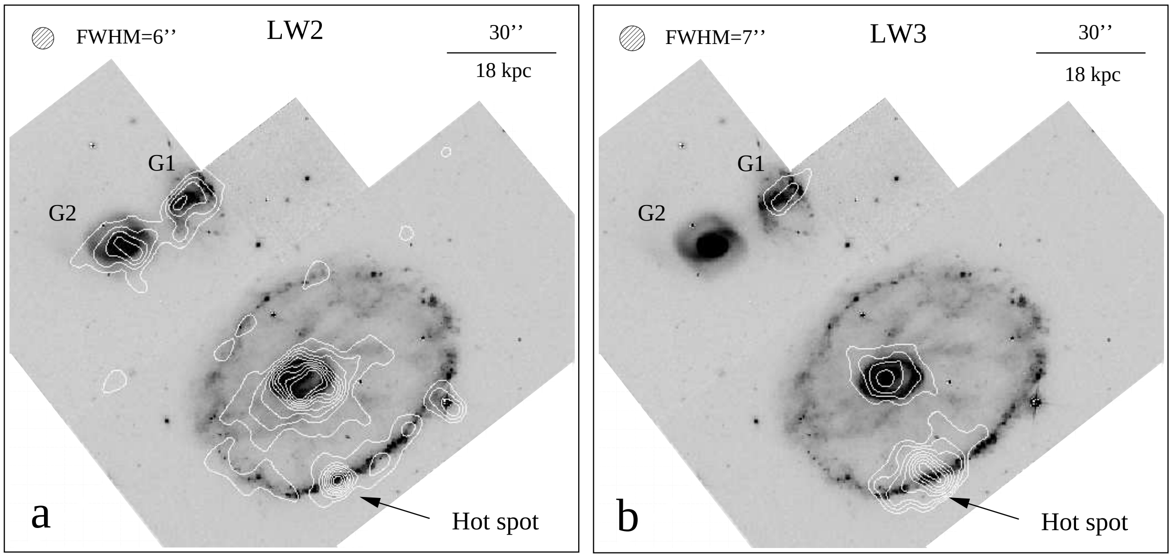

Figure 2. *The Cartwheel: a) Contour map of the ISOCAM LW2 emission overlayed on an HST wide I band image. The contour levels are from 0.1 to 0.5 mJy/pixel with a step of 0.05 mJy/pixel. b) Contour map of the ISOCAM LW3 emission overlayed on the same HST image. The contour levels are 0.2, 0.3, 0.4, 0.6, 0.8, 1, 1.2 and 1.4 mJy/pixel. North is up and East is left in both images.*

Since its mid-IR emission is very strong, this is the only ring galaxy studied with ISOCAM for which a complete CVF scan has been performed. The analysis and interpretation of the data is still in progress. However, we present here one of the most interesting results, that is the identification in the mid-IR of the AGN signature from the Seyfert nucleus. The details of this method are discussed in Laurent et al. (1999) and the application to Arp 118 is presented in Fig. 3.

4. CONCLUSIONS

Our analysis of a sample of these three ring galaxies suggests that:

1) Most of the mid-IR emission (the nucleus of the Cartwheel being the only exception) is associated with the star forming regions of the galaxies.

2) The broad band mid-IR colors of Arp 10 are typical of those found is star forming regions of late type spirals. There is a one to one correspondence between the Hα and mid-IR emission.

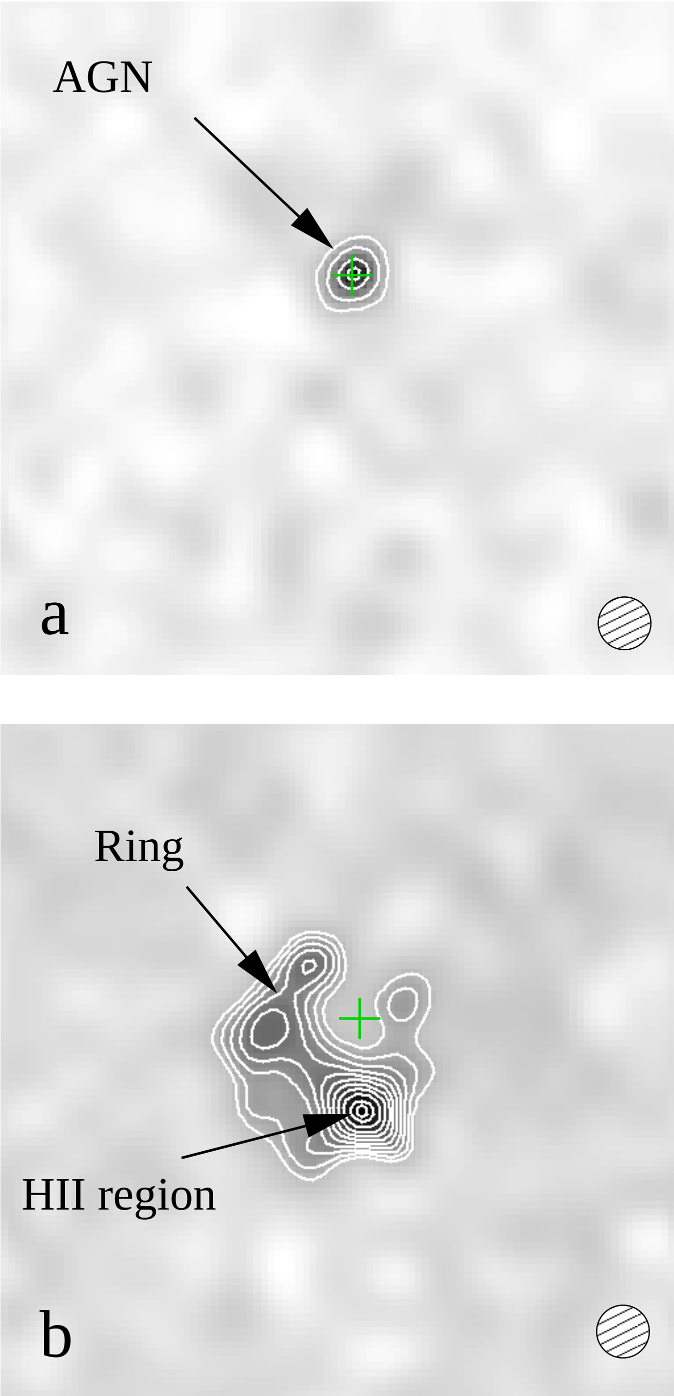

Figure 3. *Arp 118: a) Intensity map of the ISOCAM CVF [5.1-6.7] μm continuum emission. Only one source is detected and it coincides with the Seyfert 2 nucleus of the galaxy marked with a cross. b) Intensity map of the PAH emission in the same range as before with the hot AGN continuum subtracted. The peak emission coincides with the giant extranuclear HII region (see Gao et al. (1997) for more details and images).*

3) A large fraction of the mid-IR emission of the Cartwheel, is associated with the inner ring and nucleus, in stark contrast to that expected from optical emission-line studies (where most of the line emission originates from the outer ring). Recently faint Hα emission has been detected from the inner ring and it is possible that this may be due to a low-level star formation which heats the grains. However, in order to explain why the nuclear emission is so powerful compared with that of the outer ring at ISOCAM wavelengths, it seems that the dust in the outer ring must be spatially distributed very differently. One possibility is that the grains in the outer ring experience a significantly diluted UV radiation field because they are lifted out of the disk by stronger stellar winds. Alternatively, the nuclear regions may be heated by a very different process than the outer, for example shock waves from infalling clouds (Struck *et al.* 1996). Recent detection of molecular gas (Horellou *et al.* 1998) further strengthens the probability of this scenario.

4) The CVF spectrum of Arp 118 clearly suggests that the UIB features are associated with the massive star forming regions of the ring. A hot continuum emission [5.1–6.7] μm from the Seyfert nucleus is detected in agreement with the classification scheme proposed by Laurent et al. (1999).

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