Adaptive Optics spectro-imaging of starburst galaxies

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Abstract

As part of an ongoing program started at the Canada–France–Hawaii Telescope, we have observed Arp 299 and NGC 7469 in broad and narrow bands with PUEO, the facility adaptive optics system.

Locating precisely the regions where starburst activity occurs can help to understand the events that may have led to enhanced star formation. Previous results [Rouan, 1998a], [Lai etal, 1998a] have shown that starburst activity is fragmented, either in very dense star clusters or in well defined regions such as rings or interface regions.

We report on new images of Arp 299 and NGC 7469 obtained in narrow band filters (H_2, Brγ, both redshifted at z=0.01). Such an attempt to obtain spectral information at high angular resolution allows us to identify the contribution of each hot spot in terms of star formation – more accurately than broad band color-color diagrams (chromatography): does the flux come from a population of hot recently-formed young stars? from ionized gas? from an older population of stars? More importantly, are there global similarities amongst these very different galaxies?

In other words, are these high angular resolution images starting to hint at some fundamental and characteristic features of starburst galaxies?

1 Arp 299

1.1 Fact sheet

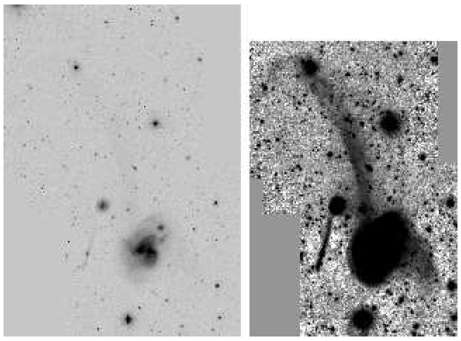

Figure 1: R band image (3×600 seconds) obtained at the UH88" [Hibbard & Yun, 1995]. The field of view is 6'×5'. The tidal tails show violent signs of interaction.

Arp 299 (11h23m37s +58°51'14" (1950)) is the merging of two galaxies, NGC 3690 to the west and IC 694 to the east (figure 1). The distance of Arp 299 is 41 Mpc (z=0.01) which provides a linear scale of 200pc/arcsecond. This

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galaxy has been classified as an Ultra–Luminous InfraRed Galaxy, with an infrared luminosity $L_{IR} \simeq 8 \times 10^{11}\,L_\odot$ [Carico et al., 1988]. The V magnitude of the nucleus of NGC 3690 is around 13, and with sufficient contrast to allow for a curvature based [Roddier et al, 1991] adaptive optics system, such as Pueo [Lai etal, 1997], to use it as a guide star [Lai etal, 1998a].

HST images have been obtained with FOC (see for instance [Vacca, 1997]), but the high absorption in this system makes source identification difficult. We have also used WFPC2 images available in the public domain to combine our broad band K images [Lai etal, 1998a] as shown on figure 2.

Figure 2: True color image of Arp 299, produced by combining an HST V band image (blue) and a Pueo K band image (red). More details can be found in [Lai etal, 1998a]. The remarkable feature is that the brightest infrared sources are invisible on the HST image, and that the numerous knots surrounding the nucleus and starburst regions are intrinsically very bright.

1.2 New Broad Band Results

Using the new KIR detector [Beuzit, 1998], it is now possible to image the entire interacting system in one exposure (whereas previous results required mosaicing), allowing to obtain much deeper images. Shown on figure 3 are deep J and K images obtained on the nights of December 13^{th}–16^{th} 1997. The exposure times are 8 × 200 seconds for the K image and 4 × 600 seconds for J image. The resolutions are 0.3" and 0.25" in these respective wavebands; each image has been slightly deconvolved, mostly to increase the Signal–to–Noise ratio. In J band, a linear deconvolution was applied with a PSF observed just after the observations (PSF reconstruction from the wave–front sensor data [Véran etal, 1997] provides only an accurate measure on brighter reference sources). In K band, the seeing had changed sufficiently between the image and the PSF acquisitions that a myopic deconvolution algorithm was used, and provided very good results. The wealth of details is impressive: there are many knots (some of which had already been previously detected), and a bridge of gas is seen both in K band and in J band.

These images have been combined in figure 4 to provide a more synthetic view of the system, with blue (J band) showing the stellar contribution (and some absorption in IC 694 and in the interface region – seen as dust lanes) and the red image showing the active regions of star formations, deeply embedded and absorbed.

At this stage, no formal photometric or chromatographic analysis has been performed, and these results should be seen as an observation report; more information can be found in [Rouan, 1998a]. However it appeared to the authors that there was an interesting morphological comparison to be drawn between Arp 299 and the famous "Antennae" galaxy, NGC4038/39.

1.3 Comparison to HST and ISO results: the Antennae galaxy

Figure 5 shows a wide field image revealing tails similar to those shown on figure 1, while the HST true color image [Whitmore & Schweizer, 1995] shows two bright nuclei, both of which are fairly red. As can be seen form figure 4, this situation is fairly similar in Arp 299. Furthermore, the interface region between NGC 4038 and NGC 4039 has many dust lanes and an apparently high absorption; this is confirmed by the ISO image [Mirabel etal, 1998] where the most luminous knot is at the interface region. Our images show a faint source (named C') at the position of a strong radio source. One can also point out that one of the galaxies (NGC 4038) has retained a ring/spiral structure (similar to IC 694), while the other (NGC 4039) is elongated and apparently more distorted by the interaction, such

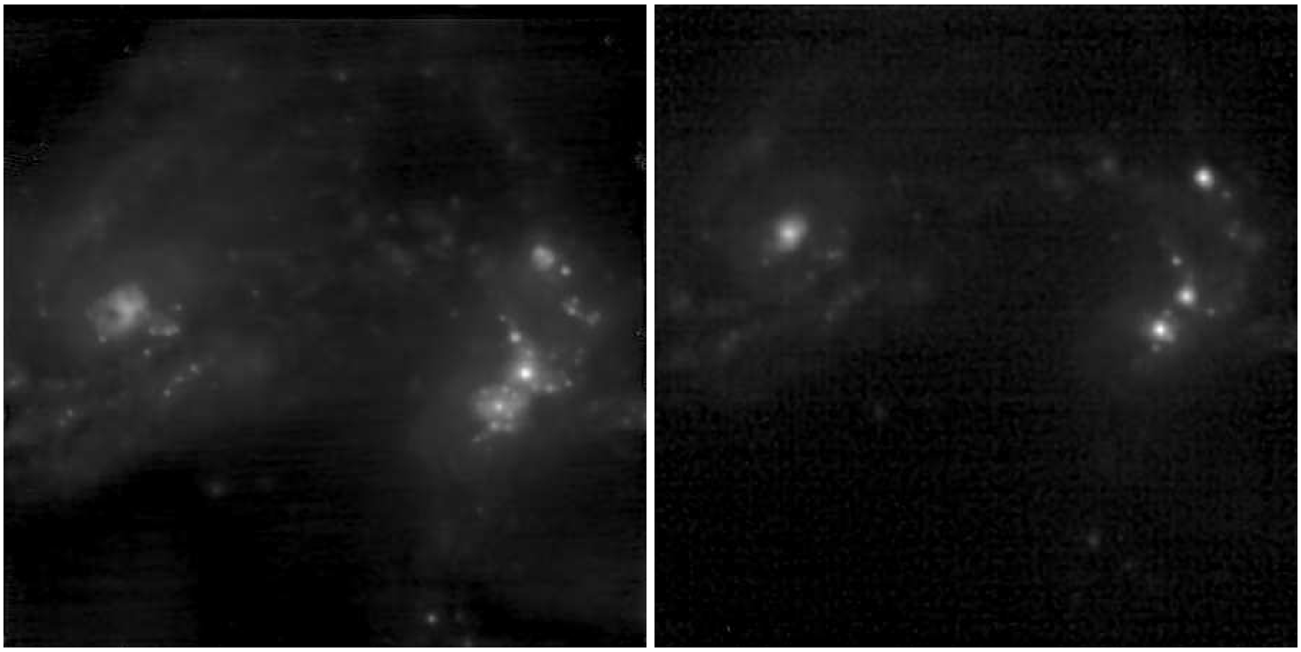

Figure 3: *Left* Deconvolved J band image of Arp 299. Exposure time is 4 × 600 seconds, and the resolution is 0.25". *Right* Deconvolved K band image of Arp 299. Exposure time is 8 × 200 seconds, and the resolution is 0.3". North is up and East to the left, and the FOV is 34"×34". Note the many knots and the bridge of gas linking NGC 3690 (on the right) and IC 694 (on the left).

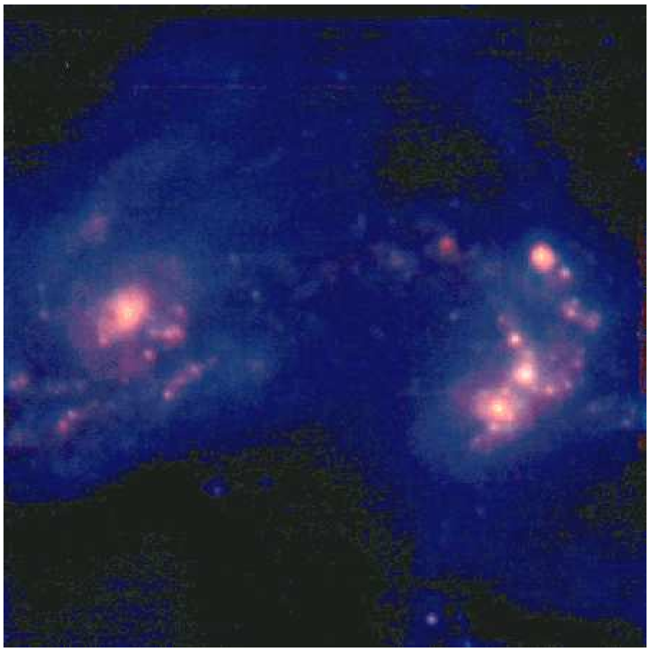

Figure 4: True color image of Arp 299, with blue as J band, tracing stellar contribution and red as K band, indicating region of starburst activity.

as NGC 3690. One might add a cautionary note, as the scales involved here are not quite similar, the separation between the nuclei in Arp 299 is 4.2 kpc, while it is of the order of 20kpc in the Antennae galaxy.

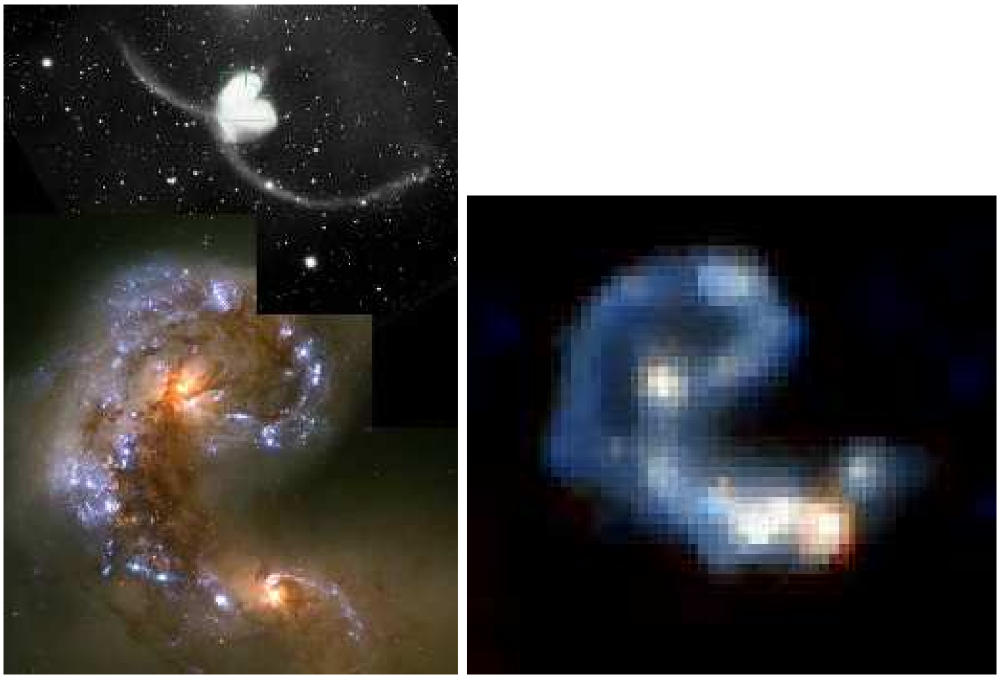

Figure 5: Antennae galaxy (NGC 4038/39) as seen by HST [Whitmore & Schweizer, 1995] and ISO [Vigroux etal, 1996], [Mirabel etal, 1998] at 6.7μm and 15 μm. There are many morphological similarities between this interacting galaxy and the Arp 299 merging galaxy.

1.4 Narrow Band Imaging

These are some preliminary results, as we encountered a calibration difficulty while reducing the data: as we do not resolve the two observed lines (Brγ and H_2) with our filters, there is substantial contribution from the continuum emission. The spectrum of the calibration stars therefore have to be known so that the effective photometric calibrations can be computed accurately enough so that even a slight gradient in the continuum will not disrupt the line contribution. So far, this has not been done, and the value of the background has been adjusted using standard photometric calibration to a first order, and then a fine tuning was performed by looking for a minimum in the amount of structure after subtraction of the continuum to the narrow band image.

Figure 6 shows the raw (cosmetically cleaned) images. The exposure time on the H_2 image was 4×400 seconds, and the resolution is 0.13", i.e. diffraction limited. The Brγ image was obtained on a different night (December 24^{th} 1997) when the seeing was considerably worse, and so the resolution is slightly worse ($\sim$ 0.4") leading to longer exposures (4×600 seconds). Linear deconvolution was applied to these images (and to the continuum images, not show here). The narrow line images are shown in figure 7.

From these images, it seems that most of the molecular hydrogen is to be found in the nucleus of NGC 3690, and not so much in the interface regions or in IC 694; this of course, could be a calibration problem, but source B2 (the nucleus of NGC 3690) is not the site of strong star formation [Gallais, 1991]. Also noteworthy are the facts that IC 694 seems to be resolved (South–East to North–West elongation) and certainly has complex extended emission surrounding it. The HII, traced by Brγ, on the other hand seems to be concentrated in regions B1 and C, the two strong starburst regions above and below the nucleus of NGC 3690. Source C', along the bridge appears to be a location of ionized hydrogen. In fact, if the comparison with the Antennaes holds true, this ought to be the place of the strongest (but mostly hidden by high absorption) star formation. We also note that the emission around IC 694 is more diffuse in Brγ than in H_2. In [Lai etal, 1998a], we debate as to whether source A contains an active

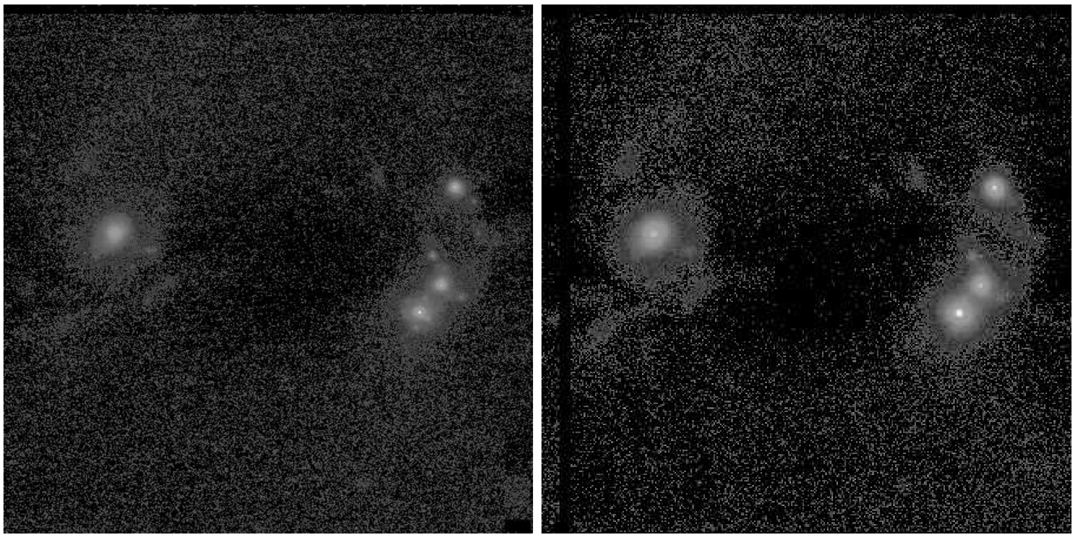

Figure 6: *Left*: H_2 raw (cosmetically cleaned) image. This image still contains the continuum emission; the exposure time was 4×400 seconds, and the FWHM is 0.13". *Right*: Brγ image. The seeing being worse, the final resolution is only 0.4", and hence the total integration time was increased to 4×600 seconds.

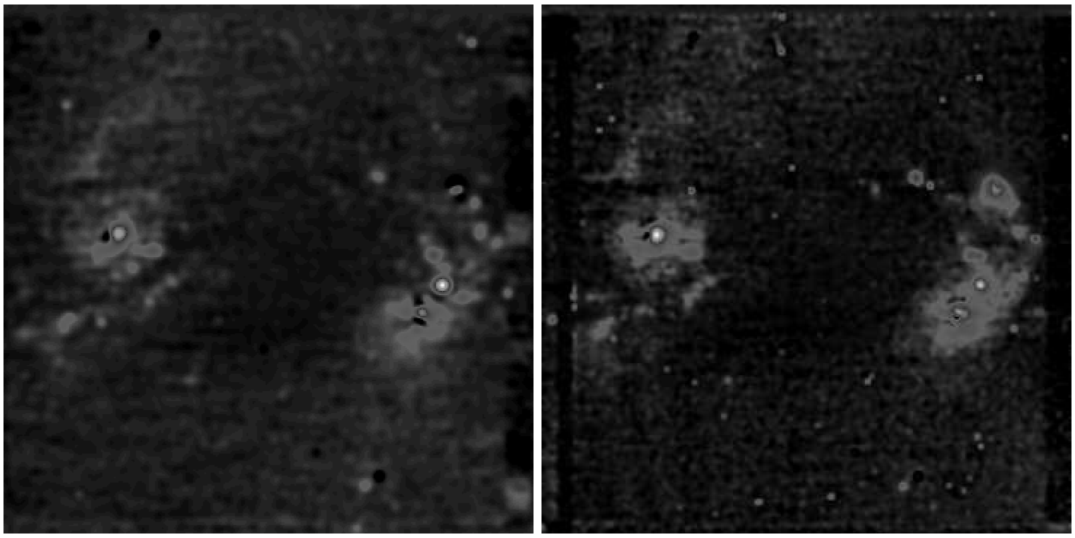

Figure 7: *Left*: H_2 – continuum emission (deconvolved, but resolution degraded to increase SNR). *Right*: Brγ – continuum, deconvolved.

nucleus or whether it is the site of a compact starburst; we argue in favor of the latter, and these new observations corroborate this: Brγ probes recent bursts of massive star formation, produced by HII regions surrounding OB stars.

2 NGC7469

2.1 Fact Sheet

NGC 7469 (23h00m44s +8°36'16s (1950)) is part of an interacting system known as Arp 298 (NGC7469 + IC5283). The companion galaxy can be seen on figure 8; it is 26 kpc away in projection. The pair is at a distance of 64 Mpc (z=0.016) producing a linear scale of 310pc/arcsecond. NGC 7469 has a Seyfert 1 nucleus, whose V magnitude is 13.1 and certainly pointlike enough to allow guiding the adaptive optics. Surrounding this bright source is a faint extended circumnuclear starburst ring.

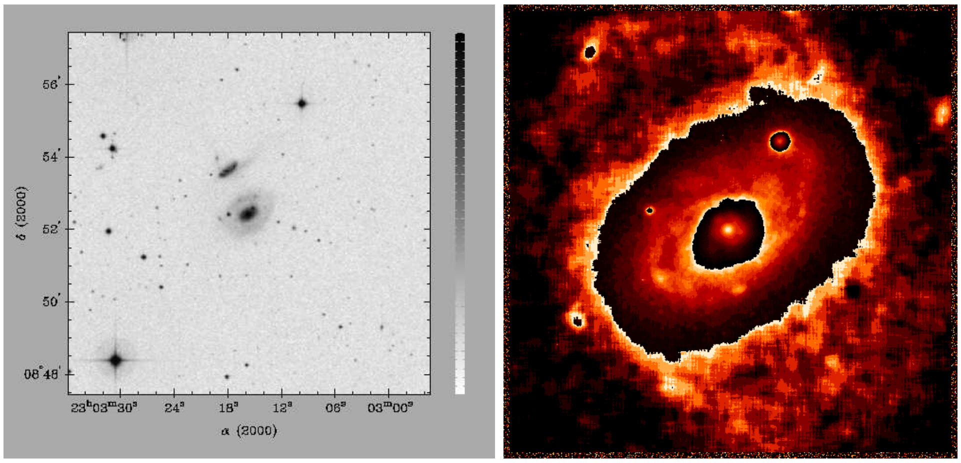

Figure 8: *Left*: NGC 7469, from the Digital Sky Survey; the FOV is 10'×10' and the companion galaxy IC 5283 is clearly visible, 26kpc in projection to the North–East. *Right*: The complete galaxy in V Band as seen by HRCam (High Resolution Camera – precursor of Pueo, tip–tilt system at CFHT). There appear to be spiral structures at many scales, not dissimilar to what is found in NGC 1068 [Rouan etal, 1998b]. The circumnuclear starburst ring is visible around the nucleus.

One of the main reasons that NGC 7469 has been studied in great detail is because it is one of the galaxies where the relative contributions to the luminosity of the active nucleus and the starburst are clear and distinct. In trying to understand the possible link between starbursts and AGNs, it is one of the most striking examples of both activities occurring simultaneously, yet at different locations. The main interest therefore lies at the region of interface, with many unanswered questions, such as: How is matter carried from the starburst ring to the nucleus to feed the massive black hole? Does the Seyfert nucleus benefit from the high density of gas and stars surrounding it in the starburst ring? And of course, what is the mechanism that started these two processes: is it one and the same? or is either one of these processes the cause of the other?

2.2 Previous Results

NGC 7469 was observed during the commissioning runs of the adaptive optics bonnette Pueo [Lai, 1996]. These images (figure 9) are on the World Wide Web (`http://www.cfht.hawaii.edu/manuals/aob/best_pictures.html`), and a paper is in preparation [Lai etal, 1998b].

These images (as compared to speckle results obtained previously, see for example [Genzel etal, 1995]) allow to probe the starburst mechanism much further in terms of morphology; instead of simple disk model, this region clearly appears as tightly wound spiral arms, with many knots and hot spots. One interesting feature is that each one of these hot spots has a counterpart in the visible (HST) image (figure 10).

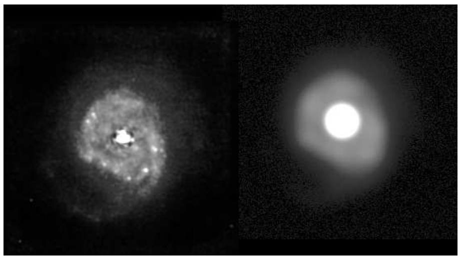

Figure 9: The nucleus of NGC 7469 before and after adaptive optics correction. The model used to interpret these to images changes from a simple disk geometry to an intricate set of tightly wound spiral arms as the resolution is increased.

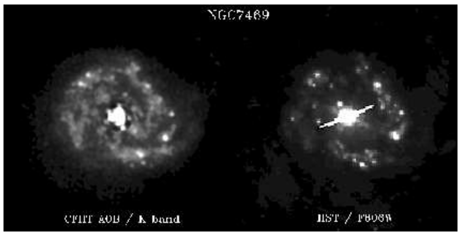

Figure 10: The nucleus of NGC 7469 as seen by the Pueo adaptive optics system and as seen by HST. Even though the wavelengths are quite different, nearly every bright knot at one wavelength has a counterpart at the other.

3 New Results

The new K band image (used for continuum subtraction) has a 40×20 seconds integration time, but with a resolution of 0.2". Deconvolution produces figure 11. With the H_2 filter (redshifted at z=0.01), the integration time was 4×300 seconds, and the FWHM 0.14". Here again, we are faced with the difficult problem of continuum subtraction, and only a first order photometric calibration was applied. The results of the H_2 – continuum is shown of figure 11. The dark ring around the nucleus is (almost certainly) due to ringing effects and unequal resolutions of the narrow band and continuum images. (Note in the following, the field of view of all the images is 4.3" $\times$ 4.3".)

These images were then combined with the previous images to obtain true color information (figure 12). The composite image on the left was produced with the K band image (red), the H_2 (green) and the HST image (blue); the H_2 seems to closely follow the hot spots. The inner ring–like structure is most likely a deconvolution artifact, but better calibrations are needed to find out whether there might not be a decrease of molecular hydrogen as we get closer to the active nucleus, or even some physical process sweeping out the H_2 from the inner regions. The image on the right is a true color composite made out of the same K and HST image, but at highest resolution. It illustrates how the data from the two instruments can be used together, and the complementarity of the two wavelength domains.

4 Conclusion

We have presented new broad (J and K) and narrow (H_2 and Brγ) bands images of Arp 299, and some new narrow band (H_2) images of NGC 7469. These are still preliminary results, and this paper should be construed as an observing report: work on the physical analysis and on the calibrations is still in progress. We want to emphasize though, the importance of being able to use adaptive optics on faint sources such as AGNs or starburst galaxies, because of the wealth of information that can be found by coupling infrared imaging with high angular resolution. Plans to provide full infrared spectroscopic capabilities (with a scanning Fabry–Perrot) are under development [Rouan, 1998b], and will add a dimension to the study of starburst galaxies with adaptive optics.

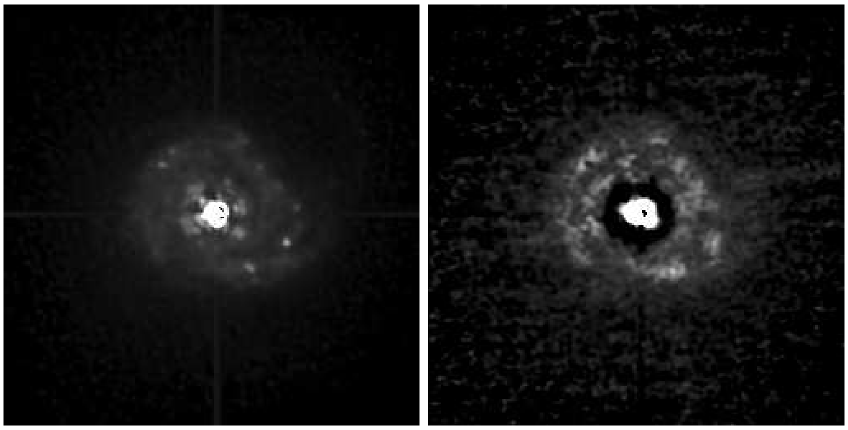

Figure 11: *Left*: K band deconvolved image of NGC 7469. the resolution on the original image was 0.2", but the structures reconstructed are very similar to the ones found previously. *Right*: First order subtraction of the continuum to the H_2 image. The dark ring around the nucleus is almost certainly an artifact.

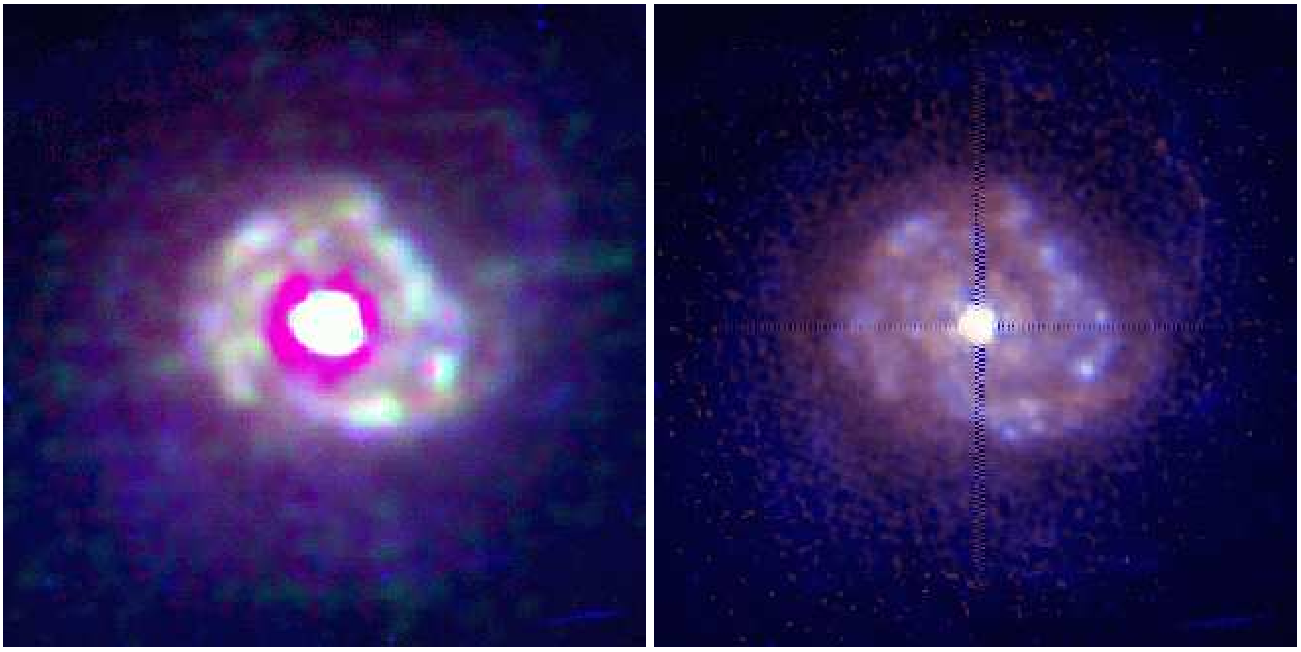

Figure 12: *Left*: True color image including the K band image (red), the H_2 image (green) and the HST image (blue). All the resolutions have been degraded slightly to match one another. *Right*: This true color image was done only with the HST and the K band image, but at the highest resolution possible.

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