Astron. Astrophys. 333, L1–L4 (1998)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

The dark side of star formation in the Antennae galaxies

I.F. Mirabel[1], **L. Vigroux**[1], **V. Charmandaris**[1], **M. Sauvage**[1], **P. Gallais**[1], **D. Tran**[1], **C. Cesarsky**[1], **S.C. Madden**[1], **and P.-A. Duc**[2]

[1] CEA/DSM/DAPNIA Service d'Astrophysique F-91191 Gif-sur-Yvette, France
[2] ESO, Karl-Schwarzschild-Strasse 2, D-85748 Garching bei München, Germany

Received 18 December 1997 / Accepted 3 February 1998

Abstract. We compare mid-infrared images of the Antennae galaxies (NGC 4038/39) from the Infrared Space Observatory, with optical images from the Hubble Space Telescope. The mid-infrared observations show that the most intense starburst in this colliding system of galaxies takes place in an off-nucleus region that is inconspicuous at optical wavelengths. The analyses of the mid-infrared spectra indicate that the most massive stars are being formed in an optically obscured knot of 50 pc radius, which produces about 15% of the total luminosity from the Antennae galaxies between 12.5 μm and 18 μm. The mid-infrared observations reported here demonstrate that the interpretation of star formation properties in colliding/merging systems based on visible wavelengths alone can be profoundly biased due to dust obscuration. The multiwavelength view of this nearby prototype merging system suggests caution in deriving scenarios of early evolution of high redshift galaxies using only observations in the narrow rest-frame ultraviolet wavelength range.

Key words: galaxies: individual: NGC 4038/39 – galaxies: individual: Antennae galaxies – infrared: interstellar: continuum – stars: formation

1. Introduction

One of the most important recent discoveries in extragalactic astronomy has been the identification of a class of "infrared luminous galaxies" ($L_{bol} \geq 10^{11}$ $L_\odot$), which emit more energy in the infrared (5–500 μm) than in all other wavelengths combined (see review by Sanders & Mirabel, 1996). The trigger of the intense infrared emission appears to be the interaction/merger of molecular gas-rich spirals. Although the spectrum of the integrated radiation from these galaxies suggests that the bulk of the luminosity arises in regions that are heavily obscured by dust, the actual distribution of the mid-infrared emission with high spatial resolution is poorly known.

The Infrared Space Observatory (ISO, Kessler et al., 1996) offers unprecedented capabilities with respect to the Infrared Astronomical Satellite (IRAS). In the mid-infrared (5.5μm - 16.5 μm) the Infrared Space Observatory Camera (ISOCAM) provides an improvement in sensitivity of $\sim$ 1000, and an increase in spatial resolution by a factor of $\sim$ 60. Furthermore, observations with arcsec resolution in spectrophotometric mode with Circular Variable Filters (CVFs) permit us to infer the nature of the optically invisible stars that heat the dust and ionize the gas.

Here we present for the first time an image of NGC 4038/39 (Arp 244 = VV 245 = 'The Antennae') in the LW3 (12 -17 μm) filter with 1.5$''$ pixel field of view and compare it with the HST optical image. An extensive account of all the ISOCAM observations will be given in a forthcoming paper by Vigroux et al (1998). The Antennae is a prototype nearby merger system of two late-type spiral disk galaxies with nuclei separated by $\sim$ 6.4 kpc. At a distance of 20 Mpc the total infrared luminosity measured by IRAS is 10^{11} $L_\odot$, which is about five times the luminosity of the system at visual wavelengths. Molecular gas observations with a resolution of 6$''$ (Stanford et al. 1990) showed that $\sim$ 60% of the CO(1-0) emission from the overall system (Sanders & Mirabel 1985) is concentrated in the two nuclei and in an extended off-nuclear complex where the two disks overlap. The spatial distribution of the CO emission is consistent with the λ6 cm and λ20 cm radio continuum maps by Hummel & van der Hulst (1986).

2. Observations and data analysis

First observations of the Antennae with coarser resolution were obtained during the Performance Verification phase (Vigroux et al. 1996). The new ISOCAM results presented in this paper consist of a large raster map obtained with the LW3 (12–17 μm) filter using 1.5$''$ pixel field of view, with a full width at half max of the observed point spread function of 4.5$''$. Full CVF scans were also made from 5.5 μm to 16.5 μm using the smallest possible increment, 0.1 μm step and 6$''$ pixel field of view (Vigroux et al. 1996).

The data analysis was performed using the CAM Interactive Analysis (CIA)[1] Software. For the raster map, dark subtraction

[1] CIA is a joint development by the ESA astrophysics division and the ISOCAM consortium led by the ISOCAM PI, C. Césarsky, Direction des Sciences de la Matière, C.E.A., France

was performed using a model of the secular evolution of ISOCAM's dark current (Biviano et al., 1997). Removal of cosmic ray induced spikes was performed using a multi-resolution median filtering technique (Stark et al. 1996). The data cube was then corrected for the memory effect of the LW detector using the inversion algorithm described in Abergel et al. (1996). As the raster was rather large, 5×5 pointings, the flat-field was built from the median off the sky positions of the galaxies.

3. Comparison of the mid-infrared and optical images

The LW3 flux (12–17 μm) is shown in Fig. 1 in red contours superimposed on the HST WFPC2 combined images in the V (5252 Å) and I (8269 Å) filters by Whitmore et al. (1997). The infrared emission appears to be associated with the nuclei of both galaxies, the star forming ring in the northern galaxy NGC 4038, and with the relatively obscured overlap region of the two disks, which is $\sim$ 5x3 kpc in extent. The emission is very clumpy and bright knots dominate the mid-infrared emission, which as discussed below, comes from gas and dust heated by massive stars.

The two optical nuclei are detected as bright knots in the mid-infrared, but the brightest knot in the 15 μm map is $\sim$ 2.3 kpc east of the nucleus of the southern galaxy NGC 4039. This knot is toward the southern corner of the region of overlap of the two disks. In this region, several optical red objects were found (Whitmore & Schweizer, 1995) associated with discrete intensity peaks in the centimeter continuum maps (Hummel & van der Hulst, 1986) and millimeter CO maps (Stanford et al. 1990). The 5x3 kpc overlap region contributes about half of the 2.16 Jy flux radiated from the whole system at 15 μm. An average extinction of $A_v \sim 70$ mag in the overlap region has been derived by Kunze et al. (1996) using SWS ISO observations. A mean absorption of $A_v \sim 73$ mag was independently inferred by Stanford et al. (1990) from CO interferometric observations.

At 15 μm the brightest area of the overlap region, located east of the nucleus of NGC 4039, is resolved into two peaks separated by 6″. The fainter one has a bright WFPC2 visual counterpart. However, the brighter eastern peak in the 15 μm map has only a faint I band counterpart of $\sim$ 48 pc in effective radius (Whitmore & Schweizer, 1995), but no conspicuous V band counterpart is seen in the HST image of Fig. 1. The brighter eastern knot alone contributes $\sim$15% of the total luminosity at 15 μm and at this wavelength it is almost 100 times brighter than the nearby nucleus of NGC 4039 (Vigroux et al. 1996). From J, H, and K band images (Duc & Mirabel, 1997), we measure an excess of $A_v \sim 7$ mag in the visual absorption in front of the eastern knot relative to the western knot.

The most luminous knots at 15 μm do not coincide with the most prominent dark lanes of the HST image. An even more striking displacement between the mid-infrared and optical dust lanes has been found in Centaurus A (Mirabel et al. 1998). These displacements could be due to different spatial distributions of the warm dust that radiates at 15 μm, and the cool dust that causes most of the optical obscuration. The dark lanes at optical wavelengths result from dust in the foreground of the optically emitting material, and projection effects also may play a role.

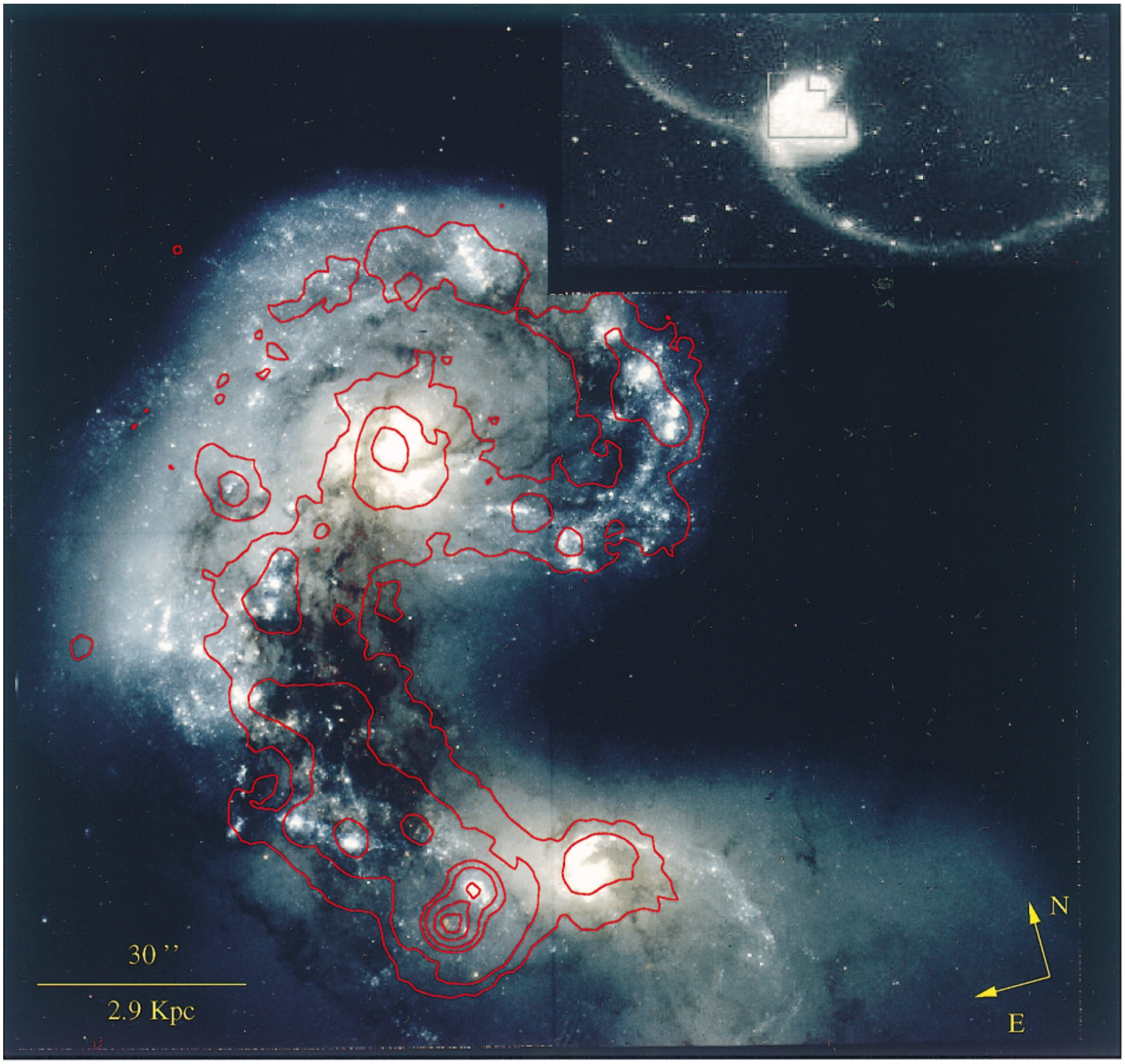
4. The most massive stars in the Antennae are not visible at optical wavelengths

We now show that one of the inconspicuous regions at optical wavelengths harbors the most massive stars in the Antennae. For this we use the imaging capability of the CVFs obtained with 6″ pixel field of view, which offers a unique opportunity to study the variation of spectral features from one area of the galaxy to the other.

In Fig. 1 we show as an example, a comparison between the CVF spectra for the brightest 15 μm peak in the overlap region and the two nuclei. The distinct characteristic of this optically obscured starburst knot is the [Ne III] line at 15.5 μm above the relatively enhanced continuum beyond 10 μm. Vigroux et al. (1996) have shown that in the Antennae the 15 μm continuum intensity is well correlated with the [Ne II] and the [Ne III] line intensities. This confirms that the enhancement of the continuum $\geq$ 10 μm is due to the thermal emission of hot dust heated by the absorption of the ionizing photons emitted by young stars. This is strengthened by the fact that the 15 μm intensity increases together with the [Ne III]/[Ne II] ratio (Vigroux et al. 1996).

For a given physical size, the [Ne III]/[Ne II] ratio is a measure of the hardness of the UV flux. The [Ne III] to [Ne II] ratio is $\sim$ 1 in the brightest area of the overlap region, and decreases to 0.1 or below in the central regions of NGC 4038 and in NGC 4039 (Vigroux et al. 1996). Using a [Ne III]/[Ne II] ratio of 1 and the diagnostic arguments by Kunze et al. (1996), a single star equivalent effective temperature of 44000 K is derived. This would correspond to an O5 main sequence star with a mass of 50–60 $M_\odot$. A more adequate treatment of star cluster evolution leads to a young cluster ($\sim 7\ 10^6$ yr) starburst with IMF extending up to 100 $M_\odot$ (Kunze et al. 1996). Therefore, using observations at optical wavelengths only, could lead to biased low values for the high mass cut-off in the IMF of interacting, luminous galaxies.

Multiwavelength observations of nearby starburst systems are instructive when deriving the morphologies of galaxy populations at high redshifts. Simulations that take into account band-shifting and surface brightness dimming by Hibbard & Vacca (1997) have shown that nearby interacting systems that are luminous in the infrared, are the best local analogs of the highest redshift galaxies found in the Hubble Deep Field (HDF). Nevertheless, at $z \geq 1.5$ the HDF is sensitive to the rest-frame UV emission, and due to the presence of an old population and/or dust it may be difficult to recover the global morphology of the underlying systems (O'Connell, 1997). If, as in the Antennae, the most intense starburst galaxies at high redshifts have substantial amounts of dust (Franceschini et al 1994; Guiderdoni et al. 1997), high sensitivity observations in the far-infrared and submillimeter wavelength bands will be needed to reveal the true global morphology of very distant galaxies.



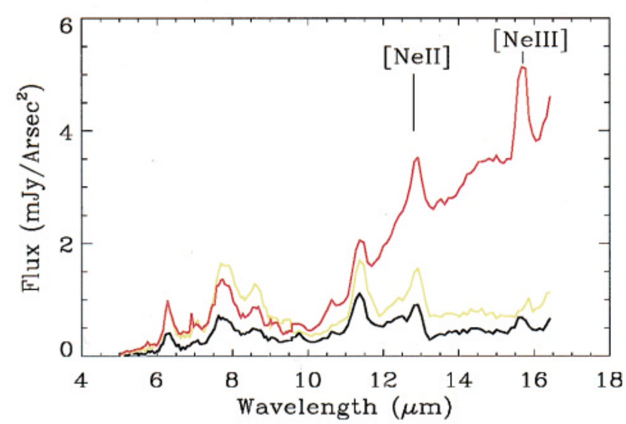


Fig. 1. The upper figure shows a superposition of the mid-infrared (12–17 μm red contours) image of the Antennae galaxies obtained with the Infrared Space Observatory, on the composite optical image with V (5252 Å) and I (8269 Å) filters recovered from the Hubble Space Telescope archive. About half of the mid-infrared emission from the gas and dust that is being heated by recently formed massive stars comes from an off-nuclear region that is clearly displaced from the most prominent dark lanes seen in the optical. The brightest mid-infrared emission comes from a region that is relatively inconspicuous at optical wavelengths. The ISOCAM image was made with a 1.5$''$ pixel field of view. Contours are 0.4, 1, 3, 5, 10, and 15 mJy. The lower figure shows spectra of the brightest mid-infrared knot (red) and of the nuclei of NGC 4038 (yellow) and NGC 4039 (black). The rise of the continuum above 10 μm and strong NeIII line emission observed in the brightest mid-infrared knot indicate that the most massive stars in this system of interacting galaxies are being formed in that optically obscured region, still enshrouded in large quantities of gas and dust.

LETTER

5. Conclusions

1) The most intense starburst in the prototype merger NGC 4038/39 takes place in an off-nuclear region that is optically obscured. This confirms the interpretation of the high far-infrared luminosity in this system in terms of star formation.

2) The [Ne III]/[Ne II] emission line ratios in the mid-infrared indicate that stars as massive as 60 $M_{\odot}$ are being formed in that optically obscured region. Therefore, to derive the high mass end of the Initial Mass Functions of the starbursts in luminous interacting galaxies, observations at wavelengths longer than the optical are needed.

3) The mid-infrared observations presented here suggest that about 15% of the bolometric luminosity from NGC 4038/39 arises in an off-nuclear region that is $\leq$ 100 pc in size.

4) The most prominent dust lanes in the optical image appear displaced from the peak distribution of the warm dust and gas traced by the mid-infrared emission. This could be due to different spatial distributions of the warm and cool dust, and/or projection effects in the optical appearance of dark lanes.

5) The infrared image also shows strong mid-infrared emission associated with the optically prominent star forming ring in NGC 4038.

6) The effects of absorption by dust are even more dramatic in the UV. Therefore, images of high redshift galaxies in their rest-frame UV could lead to strong biases in the morphological classification, and therefore in the scenarios of the history of galaxy formation.

Acknowledgements. We thank Bradley Whitmore and an anonymous referee for useful comments. This work was based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with participation of ISAS and NASA. Based on observations made with the NASA/ESA Hubble Space Telescope, obtained from data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under the NASA contract NAS 5-26555.

References

Abergel, A., Bernard, J.P., Boulanger, et al. 1996, A&A, 315, L329
Biviano, A., Sauvage, M., Roman, P., E.S.A/C.E.A Technical report, December, 1997
Césarsky, C. et al. 1996, A&A 315, L32
Duc, P.-A. & Mirabel, I.F. 1997, The Messenger, 89, 14
Franceschini, A., Mazzei, P., De Zotti, G. & Danese, L. 1994, ApJ 427, 140
Guiderdoni, B., Bouchet, F.R., Puget, J-L, Lagache, G. & Hivon, E. 1997, Nature, 390, 257
Hibbard, J.E. & Vacca, W.D. 1997, AJ 114, 1741
Hummel, E. & van der Hulst, J. M. 1986, A&A 155, 151
Kessler, M.F. et al. 1996, A&A 315, L27
Kunze, D. et al. 1996, A&A 315, L101
Mirabel, I.F. et al. 1998, in preparation
O'Connell, R.W. 1998 *The Ultraviolet Universe at Low and High redshifts, ed. W.H. Waller* (AIP Press)
Sanders, D.B. & Mirabel, I.F. 1985, ApJ 298, L31
Sanders, D.B. & Mirabel, I.F. 1996, ARAA 34, 749
Stanford, S.A., Sargent, A.I., Sanders, D.B. & Scoville, N.Z. 1990, ApJ 349, 492
Starck, J.-L., Claret, A. and Siebenmorgan, R., C.E.A. Technical Report, March, 1996
Vigroux, L., Mirabel, I.F., Altiéri, B. et al. 1996, A&A 315, L93
Vigroux, L. et al. 1998, in preparation
Whitmore, B. & Schweizer, F. 1995, AJ 109, 960
Whitmore, B. et al. 1997 STScI press release