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Letter to the Editor

Exceptional H_2 emission in the Antennae galaxies: Pre-starburst shocks from the galaxy collision⋆

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Abstract. The collision of gas-rich galaxies is believed to produce strong shocks between their gas clouds which cause the onset of the observed bursts of extended star formation. However, the so far observed shock signatures in colliding galaxies can be explained essentially by winds from already existing massive stars and supernovae and thus do not give any evidence for an outstanding pre-starburst phase. Either pre-starburst gas shocks are too short-lived to be detected or one has to modify our perception of colliding galaxies. A dedicated analysis of ISOCAM-CVF mid-infrared spectral maps led us to the discovery of exceptional H_2 $\upsilon = 0$–0 S(3) $\lambda = 9.66$ μm line emission from the "Antennae" galaxy pair, which is at an early stage of galaxy collision. Its H_2 line luminosity, normalized by the far-infrared luminosity, exceeds that of all other known galaxies and the strongest H_2 emission is spatially displaced from the known starbursts regions. This implies that most of the excited H_2 gas in the Antennae must be shocked due to the collision of the two galaxies. These observations indicate that the outstanding phase of pre-starburst shocks exists, and that they might be a key to our understanding of the formation of the first proto-galaxies.

Key words. galaxies: interacting – galaxies: ISM – galaxies: starburst – galaxies: evolution – galaxies: individual: Antennae

1. Introduction

Bursts of star formation are frequently observed in gas-rich interacting galaxies, leading to a picture of different evolutionary starburst phases. Consensus is growing that after the first ignition of massive stars, further cascades of starbursts are triggered by the blast waves of massive stars and supernovae compressing the surrounding medium, as is indicated by observations of star forming regions in our Galaxy (Ögelman & Maran 1976; Elmegreen & Lada 1977). However, very little is known about the conditions immediately before the onset of the explosive star formation event, in particular the pre-starburst phase at the beginning of a cascade. Establishing basic principles thereof would be of general value.

Theoretical considerations as well as numerical simulations suggest that the ignition of starbursts requires not only dense gas reservoirs, but also shocks causing the gas clouds to collapse (Scoville et al. 1986; Jog & Solomon 1992; Barnes 2004). Although this picture is widely accepted, direct evidence for such pre-starburst shocks is yet missing due to the difficulty of observing the presumably short-lived phase itself. Any so far detected shock signatures in colliding galaxies can be explained by winds from already existing massive stars and supernovae (e.g. Campbell & Willner 1989; Kunze et al. 1996; Rigopoulou et al. 2002; Lutz et al. 2003; Ohyama et al. 2004). Furthermore, colliding systems in an advanced merger stage show already strong relicts from previous starbursts. Since it may be hard to separate regions of already ongoing starbursts from those in a pre-starburst phase, the challenge is to find a rather virgin pair of colliding galaxies where most of the gas is still on the verge of collapse.

NGC 4038/4039 is the prototype of a colliding galaxy pair, due to its long tidal tails nicknamed the "Antennae". The system is at an early stage of encounter (Toomre 1977; Mihos & Hernquist 1996). Although a luminous infrared galaxy with $L_{\rm FIR} \sim 5 \times 10^{10}$ $L_\odot$ (Klaas et al. 1997), its current star formation efficiency is yet low, with an average value $L_{\rm FIR}/M_{\rm gas}$ = 4 $L_\odot/M_\odot$ comparable to that of normal star forming galaxies (Gao et al. 2001). Of particular interest is the overlap region of the two galaxy disks which exhibits a large amount of molecular gas (Stanford et al. 1990; Young et al. 1995; Wilson et al. 2000; Gao et al. 2001), permeated by compressed magnetic fields (Chyzy & Beck 2004). There are ongoing starbursts, the most violent ones are still heavily dust-enshrouded and located south of the molecular gas concentrations (Vigroux et al. 1996; Mirabel et al. 1998). Hence, the Antennae are in a stage of

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further imminent extra-nuclear starbursts (Haas et al. 2000; Gao et al. 2001) and therefore well suited to search for pre-starburst shocks.

A well known observational signature for shocks is the line emission of molecular hydrogen (H_2) although its excited states may also be induced by hard photons from already existing starbursts or by winds from supernova explosions (e.g. Hollenbach & McKee 1989; Sternberg & Neufeld 1999). So far, H_2 line emission has been detected in three small areas of the Antennae: the two nuclei display fairly inconspicuous H_2 luminosities compared to other starburst systems (Campbell & Willner 1989), while the H_2 emission in the southern edge of the overlap region has been attributed to the active starbursts there (Kunze et al. 1996). Hence, pre-starburst shocks have to be searched for in other regions of the Antennae.

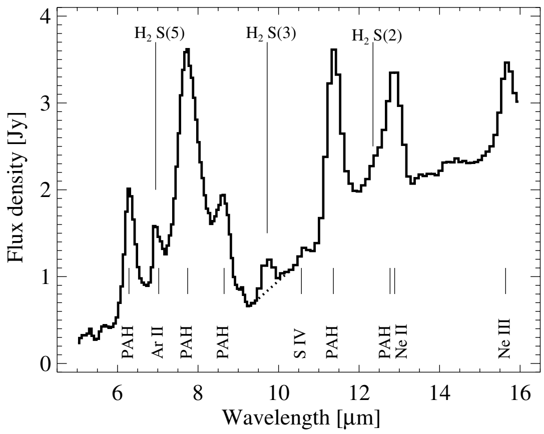

Fig. 1. Mid-infrared spectrum of the Antennae, obtained with the ISOCAM-CVF mode. It has been derived from a $2' \times 2'$ region, encompassing both nuclei and the entire overlap region. The prominent emission features are those of polycyclic aromatic hydro-carbons (PAHs) and Ne lines. Three H_2 lines are marked. While the H_2 S(5) and H_2 S(2) lines are blended with [ArII] $\lambda = 6.99\ \mu$m and [NeII] $\lambda = 12.8\ \mu$m, respectively, the H_2 S(3) line can unambiguously be detected above the continuum (dotted). The zodiacal and galactic foreground spectrum has been subtracted as derived from the $36''$ wide border of the $192'' \times 192''$ spectral maps.

2. Data

The ISO Data Archive (Kessler et al. 2003) provides valuable mid-infrared spectral maps of the entire Antennae system obtained with the ISOCAM Circular Variable Filter (CVF) mode (Cesarsky et al. 1996). Since only small portions of this data set have yet been published addressing other topics (Vigroux et al. 1996; Mirabel et al. 1998; Haas et al. 2002), we have reduced and evaluated the full 3D data cube. We checked the CVF frames and photometry by comparing with images in the 6.0, 6.7, 9.6, and 14.3 μm filters. By visual inspection we assured that the CVF frames do neither show ghost features, which may sometimes occur, nor any measurable effect of straylight within the typical calibration accuracy of about 30% (Blommaert et al. 2003).

3. Results and discussion

Figure 1 shows the 5–16 μm spectrum derived from a region, which encompasses the two nuclei as well as the overlap region in-between. Among several spectral features we focus here on the well discerned rotational H_2 line at $\lambda_{\rm obs} = 9.72\ \mu$m ($\lambda_{\rm rest} = 9.66\ \mu$m), designated in detail H_2 $v = 0$–0 S(3).

Figure 2 shows the total continuum-subtracted H_2 line map superimposed on an optical three colour image of the Antennae. Obviously, most of the H_2 line emission arises from the overlap region. While the most active starbursts are concentrated in the southern part of the overlap region (Mirabel et al. 1998) the northern part is less active displaying five times weaker starburst ionisation lines (Vigroux et al. 1996), cooler dust (Haas et al. 2000), more regular and stronger compressed magnetic fields (Chyzy & Beck 2004) and ten times fainter X-ray emission on the Chandra map (Fabbiano et al. 2000). In contrast, the H_2 line emission is evenly strong in both the southern and the northern part of the overlap region suggesting that most of the H_2 line emission is generated independently of the already active starbursts.

The continuum-subtracted H_2 line flux integrated over the entire area is 3.3×10^{-15} W m^{-2}, which corresponds to a line luminosity $L(H_2) = 4.5 \times 10^7\ L_\odot$ for a distance of 21 Mpc; correcting for a screen extinction $A_{9.7\ \mu{\rm m}} = 0.6$ mag (Kunze et al. 1996) this value rises to $8 \times 10^7\ L_\odot$. In order to estimate how much of this H_2 luminosity can be attributed to starbursts, we compare with the far-infrared luminosity $L_{\rm FIR}$, which is an ideal tracer for the power of ongoing and still dust-enshrouded star formation events. As shown in Fig. 3, the Antennae exhibit the highest $L(H_2)/L_{\rm FIR}$ ratio relative to other FIR bright galaxies; their values were determined from the ISO Archive or taken from the literature (Spoon et al. 2000; Rigopoulou et al. 2002; Lutz et al. 2003). While luminous and ultra-luminous infrared galaxies in general have extinction corrected $L(H_2)/L_{\rm FIR}$ ratios in the range of 10^{-5} to at most 10^{-4}, the corresponding value for the Antennae (1.25×10^{-3}) is more than ten times higher. Remarkably, this value exceeds even that of NGC 6240, known as the hitherto most pronounced H_2 emitter (Joseph et al. 1984; Herbst et al. 1990; van der Werf et al. 1993).

The primary suggestion, that in NGC 6240 the pre-starburst phase from the initial galaxy collision has been detected, turned out to be questionable: today the high $L(H_2)/L_{\rm FIR}$ ratio of this fairly advanced merger is believed to stem from extreme supernova winds, setting in roughly 10 million years after the previous nuclear starbursts (Tecza et al. 2000). These superwinds show up via the strong LINER spectrum and extended soft X-ray bubbles and are running now against the gas between the two nuclei causing the H_2 emission (Ohyama et al. 2003; Max et al. 2005).

In contrast, in the rather virgin Antennae the exceptionally high $L(H_2)/L_{\rm FIR}$ ratio is neither accompanied by a high total FIR luminosity nor by a warm $f_{60\ \mu{\rm m}}/f_{100\ \mu{\rm m}}$ colour typical for most active starbursts, nor by a conspicuous LINER-type spectrum (Lípari et al. 2003). Again, this suggests that the H_2 emission cannot be a consequence of already active starbursts: in case of UV fluorescence and X-ray excitation of the H_2 line and even for shocks from supernova winds one would expect that the accompanying starbursts are reflected by the far-infrared

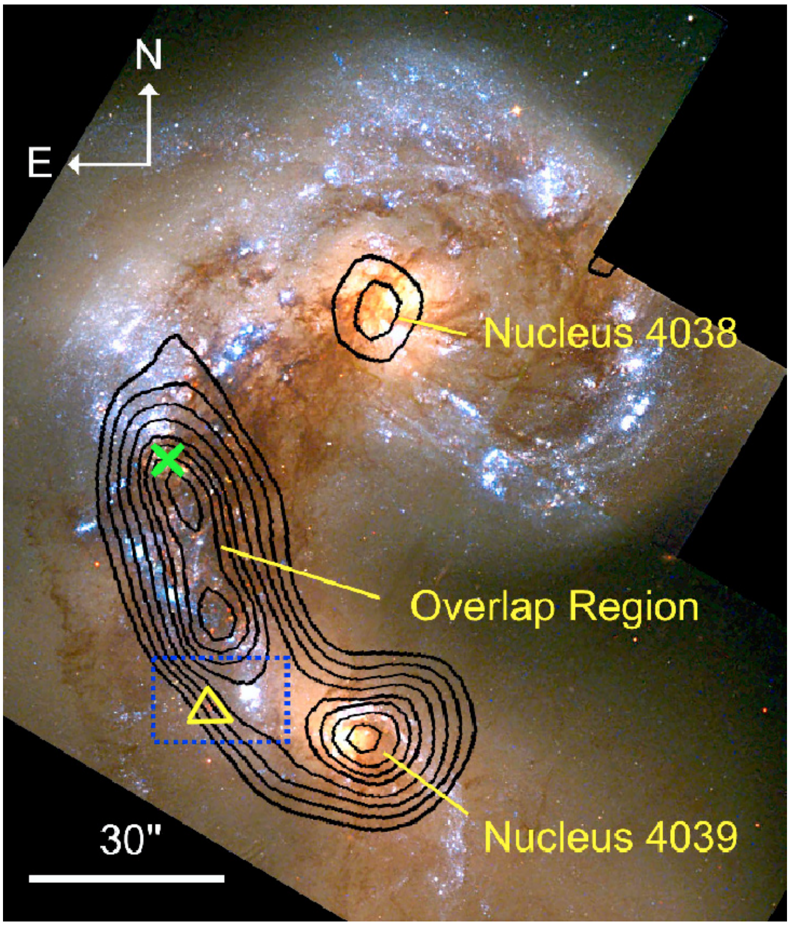

Fig. 2. Optical three colour image of the Antennae (from Whitmore & Schweizer 1995) with contours of the continuum-subtracted H_2 S(3) line emission superimposed. The contours levels are chosen in percentage of the maximum peak level at 39%, 49%, 58%, 68%, 78%, 84%, 90%, 96%. The H_2 emission, smoothed to a resolution of about 12" FWHM, extends between the two nuclei of NGC4038/4039. It is strongest in the southern nucleus and the entire overlap region of the two galaxy disks. The prominent H_2 emission is spatially displaced from the most active dust-enshrouded starbursts at the southern edge of the overlap region. In this area, marked by the dotted blue rectangle, also the H_2 S(1) and S(2) lines have been detected with ISOSWS; the yellow triangle marks the location of the main 14.3μm bright starburst region. The green cross at the northern edge of the overlap region marks the location of the peak of atomic hydrogen (HI) emission.

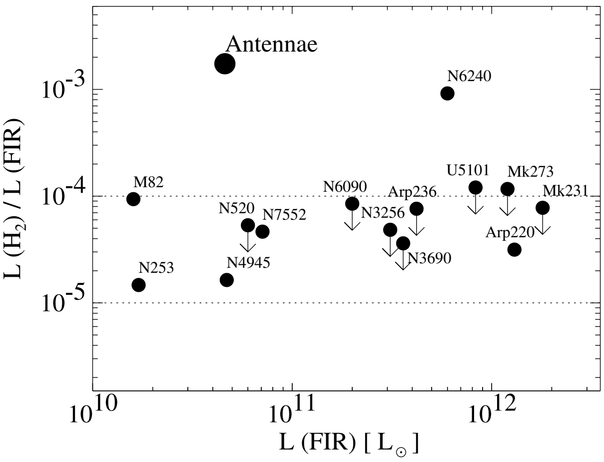

Fig. 3. Comparison of the ratio $L(H_2\ S(3))/L(FIR)$ with the far-infrared 8–1000 μm luminosity. While the Antennae galaxy system has only a moderate FIR luminosity compared with other infrared galaxies, it exhibits the highest H_2 S(3) line to FIR luminosity ratio. The horizontal dotted lines indicate the range between 10^{-5} and 10^{-4} found for infrared galaxies with obviously inconspicuous H_2 luminosity. The $L(H_2\ S(3))/L_{FIR}$ ratios of many sources are upper limits and, apart from the exotic merger N6240, the extreme starburst galaxy M82 is the only object reaching $L(H_2\ S(3))/L_{FIR} = 10^{-4}$. Less active isolated galaxies like N253 and N4945 – having 60 to 100 μm flux ratio below 0.5 – show a ten times smaller $L(H_2\ S(3))/L_{FIR}$ value of about 10^{-5}. For comparison, active starburst galaxies have $f(60)/f(100) \sim 1$, while the Antennae have $f(60)/f(100) \sim 0.7$.

luminosity, as it holds for luminous and ultra-luminous infrared galaxies with $L(H_2)/L_{FIR} < 10^{-4}$.

The exceptional $L(H_2)/L_{FIR}$ ratio together with the spatial displacement of the H_2 emission from the known vigorous starburst regions leads to the conclusion that in the Antennae much of the molecular gas is in an extraordinary phase, excited by a process not related to young stars and supernovae but originating from pre-starburst shocks running through the clouds. Since the shocks may quickly lead to the formation of massive stars having a life time in the order of 10^6 years, the phase with exceptionally high $L(H_2)/L_{FIR}$ which we see for the Antennae might be rather short-lived compared with the 10^8 years typically required for the whole merger process. Hence it is observationally rare, suggesting that such a pre-starburst phase is actually a common phenomenon during the early encounter of colliding galaxies.

At a first glance, the shocks may arise from direct H_2 cloud-cloud collisions due to the encounter of the two galaxy disks. A more detailed consideration, however, suggests that essentially the atomic HI clouds collide due to the higher impact efficiency, thereby creating an overpressure medium which leads to shocks at the surfaces of the H_2 clouds (Jog & Solomon 1992). In fact, high resolution (10″) VLA maps of the Antennae show enhanced HI emission at the northern edge of the overlap region (Hibbard et al. 2001) marked by the green cross in Fig. 2, close to the area of the bright H_2 line emission, in accordance with the overpressure model.

A rough estimate of the temperature and mass of the H_2 S(3) emitting gas of the Antennae can be obtained by standard procedures comparing with other H_2 line fluxes (cf. Sect. 3.1 in Rosenthal et al. 2000). H_2 S(5) at $\lambda = 6.91\,\mu$m is blended with the [Ar II] $\lambda = 6.99\,\mu$m line (Fig. 1). Adopting that about one sixth to one half of the observed 7 μm feature flux of 6×10^{-15} W m^{-2} is due to H_2 S(5), the temperature $T_{S(5)-S(3)}$ is about 575–825 K, a range also found for other starburst galaxies (Rigopoulou et al. 2002; Lutz et al. 2003). The mass of the molecular gas in the upper rotational level $J = 5$ is $2.6 \times 10^5\ M_\odot$.

The strength of the impending starbursts in the Antennae can be estimated from the total amount of excited molecular gas, even at cooler temperatures emitting the H_2 v = 0–0 S(1) line. H_2 S(1) line observations are only available for a small $14'' \times 27''$ area in the southern overlap region. For the entire Antennae we therefore extrapolate the H_2 S(1) line luminosity from these ISOSWS observations (Kunze et al. 1996). For this extrapolation we adopt a constant H_2 S(1) / H_2 S(3) ratio across the Antennae. Since this ratio might be higher in less active regions outside the area covered by the ISOSWS observations, this is a conservative assumption leading to a lower limit on the actual H_2 S(1) luminosity. We find that about 10% of the Antennae's total H_2 S(3) emission arise from the $14'' \times 27''$ area. If also the H_2 S(1) emission from this ISOSWS area makes up 10% of that in the $2' \times 2'$ area, the mass of excited H_2 observed in the S(1) transition at a temperature $T \sim 200$ K (adopted from Kunze et al. 2000) yields about $4.9 \times 10^8\ M_\odot$ for the entire Antennae; this corresponds to about 5% of the total gas mass of $9.6 \times 10^9\ M_\odot$ as derived from CO observations covering a comparable area (Young et al. 1995). An open issue is whether only the currently shocked gas is transformed into stars or whether much more of the gas is involved in the future star formation process with only a small fraction being currently gripped by the shock wave. Adopting that about 20% of the shocked H_2 of $5 \times 10^8\ M_\odot$ collapses into stars during the next 10^6 years, the resulting average star forming rate is 100 $M_\odot$/year. This is an extreme value found only for ultra-luminous infrared galaxies. If the gas mass of $10^8\ M_\odot$ is converted to stars of about 20 $M_\odot$, each having a luminosity of about $10^4\ L_\odot$, the luminosity of the Antennae will increase by about $5 \times 10^{10}\ L_\odot$, hence it will be doubled. In order to become ultra-luminous much heavier nuclear starbursts are required during further stages of the merger process.

Eventually, the shock-induced star formation may have played a role in the evolution of proto-galaxies in the early universe at a redshift $z \sim 20$. The very first stellar generation with zero metallicity, the population III stars, must have formed during a short episode; otherwise their metallicity would have been raised. Due to the lack of appropriate radiative cooling via metals the kinetic energy in the gas clouds remains at a high level. Therefore, the clouds need time to accumulate the higher amount of gas required before they can collapse according to the Jeans criterion. In order to fit the constraints, strong simplifications for the processes in the early universe have to be made (e.g. Abel et al. 2002). Our results for the Antennae suggest that shocks could provide a natural trigger for speeding-up the collapse of clouds also in colliding proto-galaxies.

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References

Abel, T., Bryan, G. L., & Norman, M. L. 2002, Science, 295, 93
Barnes, J. 2004, MNRAS, 350, 789
Blommaert, J., Siebenmorgen, R., Coulais, A., et al. 2003, The ISO Handbook: Vol II. The ISO Camera, ESA-SP, 1262
Campbell, A., & Willner, S. 1989, AJ, 97, 995
Cesarsky, C., Abergel, A., Agnese, P., et al. 1996, A&A, 315, L32
Chyzy, K., & Beck, R. 2004, A&A, 417, 541
Elmegreen, B. G., & Lada, C. J. 1977, ApJ, 214, 725
Fabbiano, G., Zezas, A., & Murray, S. S. 2000, ApJ, 554, 1035
Gao, Y., Lo, K., Lee, S.-W., & Lee, T. H. 2001, ApJ, 548, 172
Haas, M., Klaas, U., Coulson, I., et al. 2000, A&A, 356, L83
Haas, M., Klaas, U., & Bianchi, S. 2002, A&A, 385, L23
Herbst, T., Graham, J., Tsutsui, K., et al. 1990, AJ, 99, 1773
Hibbard, J., van der Hulst, J., Barnes, J., & Rich, R. 2001, AJ, 122, 2969
Hollenbach, D., & McKee, C. F. 1989, ApJ, 342, 306
Jog, C. J., & Solomon, P. M. 1992, ApJ, 387, 152
Joseph, R. D., Wade, R., & Wright, G. S. 1984, Nature, 311, 132
Kessler, M., Müller, T., Leech, K., et al. 2003, The ISO Handbook: Vol I. Mission & Satellite overview, ESA-SP, 1262
Klaas, U., Haas, M., Heinrichsen, I., & Schulz, B. 1997, A&A, 325, L21
Kunze, D., Rigopoulou, D., Lutz, D., et al. 1996, A&A, 315, L101
Lípari, S., Terlevich, R., Díaz, R., et al. 2003, MNRAS, 340, 289
Lutz, D., Sturm, E., Genzel, R., et al. 2003, A&A, 409, 867
Max, C., Canalizo, G., Macintosh, B. A., et al. 2005, ApJ, accepted [arXiv:astro-ph/0411590]
Mihos, J., & Hernquist, I. 1996, ApJ, 464, 641
Mirabel, F., Vigroux, L., Charmandaris, V., et al. 1998, A&A, 333, L1
Ögelman, H. B., & Maran, S. P. 1976, ApJ, 209, 124
Ohyama, Y., Yoshida, M., & Takata, T. 2003, AJ, 126, 2291
Rigopoulou, D., Kunze, D., Lutz, D., et al. 2002, A&A, 389, 374
Rosenthal, D., Bertoldi, F., & Drapatz, S. 2000, A&A, 356, 705
Scoville, N. Z., Sanders, D. B., & Clemens, D. P. 1986, ApJ, 310, L77
Spoon, H., Koornneef, J., Moorwood, A., et al. 2000, A&A, 357, 898
Stanford, S., Sargent, A., Sanders, D., & Scoville, N. 1990, ApJ, 349, 492
Sternberg, A., & Neufeld, D. A. 1999, ApJ, 516, 371
Tecza, M., Genzel, R., Tacconi, L., et al. 2000, ApJ, 537, 178
Toomre, A. 1977, in The evolution of galaxies and stellar populations, ed. B. M. Tinsley, & R. B. Larson, 401
van der Werf, P., Genzel, R., Krabbe, A., et al. 1993, ApJ, 405, 522
Vigroux, L., Mirabel, F., Altieri, B., et al. 1996, A&A, 315, L93
Whitmore, B., & Schweizer, F. 1995, AJ, 109, 960
Wilson, C., Scoville, N., Madden, S., & Charmandaris 2000, ApJ, 542, 120
Young, J., Xie, S. Tacconi, L., et al. 1995, ApJS, 98, 219