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A molecular tidal tail in the Medusa minor merger

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Abstract. We have detected CO 1–0 emission along the tidal tail of the NGC 4194 (the Medusa) merger. It is the first CO detection in the optical tail of a minor merger. Emission is detected both in the centre of the tail and at its tip. The molecular mass in the 33″ Onsala 20 m beam is estimated to be $\gtrsim 8.5 \times 10^7$ $M_\odot$ which is at least 4% of the total molecular mass measured so far in this system. We suggest that the emission is a molecular tidal tail which is part of the extended structure of the main body, and that the molecular gas was thrown out by the collision instead of having formed in situ from condensing atomic material. We find it unlikely that the emission is associated with a tidal dwarf galaxy (even if the future formation of such an object is possible), but high resolution HI, CO and optical observations are necessary to resolve the issue. The Medusa is very likely the result of an elliptical+spiral collison and our detection supports the notion that molecular gas in minor mergers can be found at great distances from the merger centre.

Key words. galaxies: evolution – galaxies: individual (NGC 4194) – galaxies: ISM – galaxies: interacting – radio lines: galaxies – radio lines: ISM

1. Introduction

Although tidal tails are often very gas rich, the gas in most cases is in the form of atomic (HI) gas. Searches for molecular hydrogen in the tails of mergers and interacting galaxies were long unsuccessful (e.g. Smith & Higdon 1994). The molecular gas in a major disk-disk merger becomes heavily concentrated towards the inner kpc in most cases (e.g. Barnes & Hernquist 1996). Thus, an extended CO component in a coalesced, major merger is not expected. Recently, CO emission has, however, been found in tidal dwarf galaxies (TDGs) formed in the extended tails of interacting galaxies and mergers (e.g. Braine et al. 2000). These objects are kinematically distinct and often found at the tip of the tidal tail (Duc & Mirabel 1994). Molecular masses of 10^7–10^8 $M_\odot$ seem to be typical for TDGs. The molecular gas in these TDGs is suggested to form inside the HI clouds, and in this scenario was not expelled from the parent galaxy in molecular form (e.g. Braine et al. 2000). In the M 81 galaxy group, molecular condensations without an apparent stellar component are found in two places (Brouillet et al. 1992; Heithausen & Walter 2000). The latter object is extended over more than 1′, and could be a TDG in formation.

A collision between an elliptical and a less-massive spiral is a minor merger that leads to the formation of regular shells. Dynamical simulations of elliptical+spiral (E/S) collisions suggest that, if the gas clouds are treated as particles, a significant amount of the molecular gas may follow the disk stars into the tidal features – instead of becoming concentrated into the central kpc (e.g. Kojima & Noguchi 1997). Thus searching for molecular gas in the tidal tails of minor mergers may be a fruitful approach. In this picture, gas could also be associated with the shells which are otherwise assumed to be gas-free. Indeed, Charmandaris et al. (2000) detect CO emission in the shells of the nearby elliptical Centaurus A – which is believed to be the result of an E/S merger.

The Medusa merger, NGC 4194, (Table 1; Fig. 2) ($L_{\rm IR} = 8.5 \times 10^{10}$ $L_\odot$ at $D = 39$ Mpc) belongs to a class of lower luminosity mergers compared to Ultraluminous IR Galaxies, which have $L_{\rm IR} \gtrsim 10^{12}$ $L_\odot$. The Medusa has an extended region of intense star formation (e.g. Prestwhich et al. 1994; Armus et al. 1990), a feature that might be common for many of these "intermediate luminosity" mergers. As the name indicates, the optical morphology of the Medusa merger is spectacular with a knotty tidal tail stretching out 60″ (11.3 kpc) north of the main body.

We have studied the central starburst region of this merger in the CO 1–0 line with the OVRO array and the Onsala 20 m telescope (see Aalto & Hüttemeister 2000 (AH) and references therein) and found a surprisingly extended molecular cloud distribution (Fig. 1). A significant

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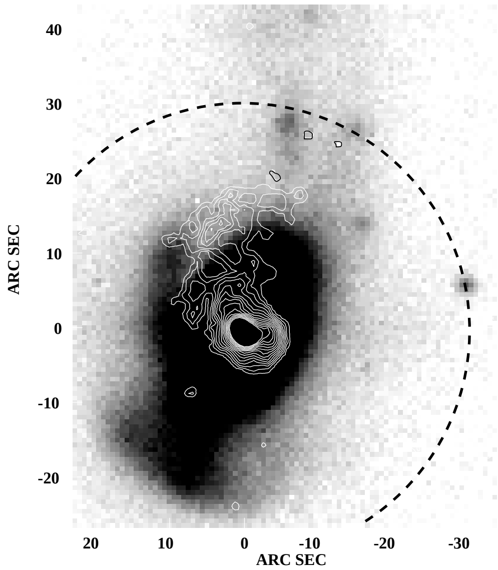

Fig. 1. Overlay of the OVRO CO (from AH) contours (white, apart from clouds in the tail marked in black) on a greyscale, overexposed optical R-band image (Mazzarella & Boroson 1993). The dotted line shows the edge of the OVRO primary beam. The contours are not primary beam corrected which means that features close to the edge of the beam are suppressed in intensity.

amount of the CO flux resides in dust lanes crossing the centre and curving into the base of the tidal tail. The morphology of the Medusa combined with the extended gas distribution led us to suggest that it is the result of an E/S galaxy collision (AH).

With the intention of investigating the notion that molecular clouds may follow the stars out to great radii in minor mergers we have searched for CO 1–0 emission in the middle and tip of the tidal tail of NGC 4194 with the Onsala 20 m telescope. We detect the presence of significant amounts of molecular gas in both positions. The observations are presented in Section two and a brief discussion of the implications of the detection in Section three.

2. Observations and results

We have obtained single dish spectra of the 1–0 transition of CO in the tidal tail of NGC 4194 with the Onsala 20 m telescope in two positions. The observations were carried out in February 2001 and the system temperature was typically 500 K. We alternated between centre velocities 2300 $\mathrm{km\,s^{-1}}$ and 2500 $\mathrm{km\,s^{-1}}$. The spectra were then joined together to get flat baselines and minimize spurious spectrometer signals. The pointing accuracy was checked on SiO masers and was found to be about $2''$. The observed positions, integrated intensities, central velocities and molecular masses can be found in Table 1. The signal in position 1 (mid-tail) is a 6σ detection and in position 2 (tip of tail) we are detecting emission at the 3σ level, due to a higher rms noise and a narrower linewidth. First order baselines have been removed in all cases. For position 2, two bad channels were removed in the raw data at $v = 2250$ $\mathrm{km\,s^{-1}}$. In Fig. 2 we show the observed positions and spectra overlayed on an R-band CCD-image (Mazzarella & Boroson 1993). The central spectrum is taken from AH.

3. Discussion

3.1. Molecular mass

We have used a standard Galactic conversion factor to estimate the mass in both the galaxy centre and in the tail. It is rather unlikely that the same conversion factor is applicable for both regions since the centre emission originates in gas involved in a starburst with associated extreme gas properties (AH). We suspect that the standard conversion factor overestimates the molecular mass in the centre, and underestimates it in the tail. It is difficult to judge by how large a factor the conversion factor varies, but we believe that the gas detected in the tail constitutes a larger fraction of the total H_2 mass than the 4% indicated by using the same factor. If the gas in the tail originated in the outskirts of the precursor spiral, a conversion factor calibrated for the outer region of disk galaxies should be appropriate (e.g. Arimoto et al. 1996).

The fact that the CO emission is detected far out in the actual optical tail sets it apart from the tidal CO detection in the minor (disk/disk) merger NGC 2782 – even if the linear distance from the centre of the galaxy may be the same as that for our detection in NGC 4194. In NGC 2782, 6×10^8 $M_\odot$ of molecular gas are associated with a depression in the optical emission at the base of the eastern tail (Smith et al. 1999).

3.2. Dynamics

From our previous high-resolution OVRO map (AH) we see that the inner region of NGC 4194 is rotating with a position angle of 160°, where the northern emission is blueshifted (even if the north-eastern part of the emission is moving at too high velocity to fit in the simple rotational pattern). The CO emission in the tidal tail is blueshifted by $\approx$100 $\mathrm{km\,s^{-1}}$ from the centre gas (see Table 1) and thus appears to be participating in the general rotational pattern of the main body. In contrast, the tidal molecular material of NGC 2782 (Smith et al. 1999) is in apparent counterrotation to the central gas which underlines the difference in merger history between NGC 4194 and NGC 2782.

3.3. A molecular tidal tail?

It is tempting to suggest that the tail emission is emerging from a TDG being born. The molecular mass indicated by the detection ($> 8.5 \times 10^7$ $M_\odot$ for the solid detection in the middle of the tidal tail) is compatible with the molecular masses that have been reported to be associated with developed tidal dwarfs in the Arp 105 and Arp 245 systems by Braine et al. (2000), which are $> 1.4 \times 10^8$ $M_\odot$ and $> 2.2 \times 10^8$ $M_\odot$, respectively. However, we suggest

Table 1. Observed positions and results[a].

Position	RA (1950.0)	Dec (1950.0)	$\int T_{\rm mb}$ (K km s^{-1})	ΔV (km s^{-1})	$V_{\rm c}$ (km s^{-1})	$M({\rm H_2})^{\rm b}$ $M_\odot$
Centre	$12^{\rm h}11^{\rm m}41.22^{\rm s}$	$54°48'16''$	17 ± 2	200	2530	$\leq 2 \times 10^9$
Tail-1	$12^{\rm h}11^{\rm m}40.00^{\rm s}$	$54°48'56''$	0.72 ± 0.12	100	2450	$\geq 8.5 \times 10^7$
Tail-2	$12^{\rm h}11^{\rm m}40.00^{\rm s}$	$54°49'12''$	0.45 ± 0.14	56	2448	$\geq 5.3 \times 10^7$

a): For $\eta_{\rm beam} = 0.5$; $\theta = 33''$.
b): This is for a conversion factor of $X = N({\rm H_2})/I(^{12}{\rm CO}) = 2.3 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$. The adopted distance is $D = 39$ Mpc.

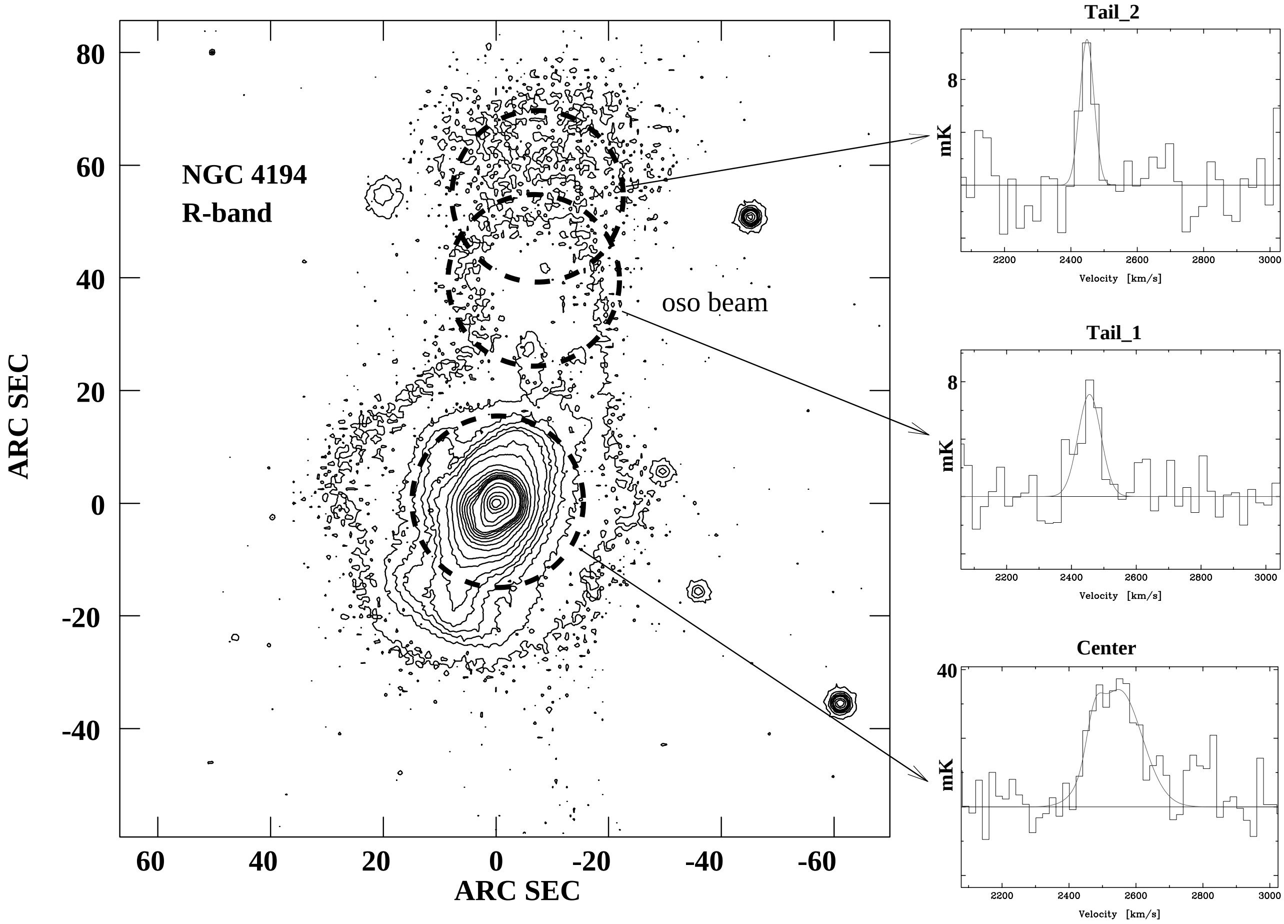

Fig. 2. To the left is a contour plot of an R-band CCD image of NGC 4194 (Mazzarella & Boroson 1993). The levels are logarithmic (in flux) to clearly show the faint structure, such as the northern tidal tail. The top and middle right panels show the two CO 1–0 spectra in the tidal tail and the bottom right panel shows the central spectrum. The temperature scale is in mK ($T_{\rm mb}$).

that the emission detected is still part of the structure in the main body and belongs to the dust lane traced by CO emission in the northern part of the main body (Fig. 2). The lane likely continues well into the tidal tail, which is suggested by the blue image in Arp's catalogue (1966). Thus, the CO emission detected indicates the presence of *a molecular tail*, perhaps as long as the optical tail. We suggest that while the future destiny of the molecular emission may well be to condense into a dwarf galaxy, this has not yet happened. However, high resolution CO and HI observations together with sensitive optical studies are necessary the emission is coming from a distinct dynamical system or not.

3.4. The origin of the gas

We suggest that the molecular gas in the tail of the Medusa was brought there in molecular form instead of having formed in situ from atomic material. Although dust lanes and CO emission are not always related, in this particular galaxy there is a very strong correlation (as shown by AH). A big fraction ($\gtrsim$30%) of the CO emission is tracing dust lanes going from the centre all the way into the tidal tail. We suggest that, since the dust lane continues into the tidal tail, the CO continues with it – and that it is part of a molecular structure that followed the stars into the tail, and remained molecular. One could of course argue that the CO-dust correlation breaks down in the tail – but since we are detecting molecular gas in the tail, it is natural to assume that it is associated with the dust.

A single dish HI spectrum (Thuan & Martin 1981) shows the bulk of the HI emission to be redshifted with respect to the tail. From the line profile, we estimate that at most 1/3 of the total HI emission is associated with the tail. However, to determine the origin of the molecular gas in the tail, both high resolution HI and CO maps are necessary. For the H_2 to have formed from the HI we expect the CO emission to be associated with column density peaks in the HI distribution. It could be argued that a more large-scale phase transition between HI and H_2 has occured in which case a small scale relation between HI and CO would not be expected. However, such phase transitions occur in high pressure environments (such as in centres of galaxies) or in shocks. The tail of the Medusa appears to be too diffuse to provide the right environment for such a transition. Thus, differences in the CO and HI distribution should support the notion that the H_2 did not form in situ. Multi-colour images in the optical will help study the structure of the dust and its association to CO in more detail.

The situation in the Medusa is very different from major mergers where the CO emission ends up collected in the inner region of the galaxy and where most of the optical body of the merger is devoid of molecular gas. The CO found in full-blown optical TDGs of such major merger systems (e.g. Braine et al. 2000) is very far from the merger centre and completely detached from it. Thus it may well have a different origin there, i.e. form from the HI tails in situ. The connection between molecular gas in tidal tails like that of the Medusa and TDGs clearly needs to be investigated further.

3.5. The fate of the gas

Armus et al. (1990) detect no Hα emission in the tail of the Medusa, so there is no indication of ongoing star formation in the molecular gas, even if a deeper study will be necessary to determine actual star formation rates. If the molecular gas in the tail of the Medusa is collected in self-gravitating clouds, but quiescent, it may survive for a longer time than the gas in the centre – which is currently being consumed by a starburst. The gas clouds need to be part of a bigger structure, such as a TDG, for them to survive when the tail disperses.

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