Formation of Molecular Gas in the debris of violent Galaxy Interactions

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In many gravitational interactions between galaxies, gas and stars that have been torn from either or both of the precursor galaxies can collect in 'tidal tails'. Star formation begins anew in these regions to produce 'tidal dwarf galaxies' [1] [2] [3] [4], giving insight into the process of galaxy formation through the well-defined timescale of the interaction. But tracking the star formation process has proved to be difficult: the tidal dwarf galaxies with young stars showed no evidence of the molecular gas out of which new stars form [5] [6] [7] [8]. Here we report the discovery of molecular gas (carbon monoxide emission) in two tidal dwarf galaxies. In both cases, the molecular gas peaks at the same location as the maximum in atomic-hydrogen density, unlike most gas-rich galaxies. We infer from this that the molecular gas formed from the HI, rather than being torn in molecular form from the interacting galaxies. Star formation in the tidal dwarfs appears to mimic that process in normal spiral galaxies like our own.

Tidal Dwarf Galaxies (TDGs) are gas-rich irregular galaxies made out of stellar and gaseous material pulled out by tidal forces from the disks of the colliding parent galaxies into the intergalactic medium [9] [10] [11] [12]. They are found at the ends of long tidal tails, sometimes 100 kpc from the nuclei of their progenitors, and host active star-forming regions. TDGs contain two main stellar components: young stars recently formed by collapse of expelled atomic hydrogen (HI) clouds, and an older stellar population, at least 1 Gyr old, originally part of the disk of the parent galaxies. Their overall gaseous and stellar properties range between those of classical dwarf irregular and blue compact dwarf galaxies, with the exception of their metallicity which is higher – typical of the outer disk of a spiral [12]. Whether a large fraction of dwarf galaxies were formed through tidal encounters in the early universe when spiral galaxies were more gaseous and less metal rich and collisions more frequent is an open question and one of the drivers to study TDGs. One way to answer this question is the dark matter content of dwarf galaxies. Observations of ordinary dwarf galaxies show that a lot of dark matter, or mass that is in some sotofar invisible form, is necessary to account for their rotation velocities. Numerical simulations of gravitational interactions indicate that TDGs should have very little dark matter [13] if the dark matter is, as currently believed, in form of a large halo and not in, say, a rotating disk. Thus, *if* TDGs are found to possess the same dark matter properties as other dwarf galaxies then powerful constraints are placed on the form of dark matter. If TDGs do *not* contain dark matter as ordinary dwarf galaxies, then tidal interactions cannot be the principal formation mechanism for these small galaxies nor can dark matter be part of galactic disks.

The observations were carried out with the 30meter telescope operated by the Institut de Radioastronomie Millimétrique (IRAM) on Pico Veleta, Spain in June of 1999. Carbon Monoxide (CO) emission is detected in the Southern TDG in Arp 105 (Figure 1 ; hereafter A105S) and main TDG in Arp 245 (Figure 2; hereafter A245N) in both the ground state CO($J = 1 - 0$) and the CO($J = 2 - 1$) transitions. Small maps were made of both sources to localise the CO emission with respect to the atomic hydrogen (HI), ionized gas (Hα), and optical continuum [3] [14]. The central (0,0) CO(1–0) spectra are shown in Fig. 3 along with the HI spectra at the same positions with a similar beamsize. The CO(1–0) luminosities and derived H_2 mass estimates (see Table 1) of A105S and A245N are far above those of other dwarf galaxies [15]. Despite the different environments, the star formation efficiency, defined as the rate of star formation per mass of molecular gas, is quite close to that observed in the Milky Way and other spiral galaxies [16].

Small CO maps have been made consisting of six positions towards A105S and four positions towards A245N. In both cases, the CO peaks at the HI column density maximum and the dynamics of the atomic and molecular components are virtually identical (Figure 3). In spiral galaxies, on the other hand, HI and CO have very different distributions (see *e.g.* [17] [18]), showing that the molecular gas that we have found in the TDGs has not simply been torn off the parent galaxies together with the HI but has formed *in situ*. Although the calculations were performed for post-shock gas, an estimate of the molecule formation time is $t \sim n^{-1}$Gyr [19] where n is the density of the atomic medium in particles cm^{-3}. Numerical simulations of Arp 245 [14] yield an age of about 100 Myr for A245N and a rough age estimate for A105S can be obtained by dividing the projected distance to the spiral by the relative radial velocity, yielding about 200 Myr [3], sufficient for H_2 formation in standard atomic hydrogen clouds ($\overline{n} \sim 10\mathrm{cm}^{-3}$). The dust on which the H_2 forms is captured from the parent galaxies and present in the atomic gas [20] [21] [22]. *The molecular gas has formed inside the HI clouds and star formation is proceeding in a standard way from the molecular gas.*

Our observations show that the molecular gas is an important component in the visible mass budget of TDGs, between $\sim 20\%$ and $\gtrsim 50\%$ of the atomic hydrogen mass (see Table 1). The fact that we detect large quantities of molecular gas and that we have every reason to believe that this gas is the result of conversion from HI into H_2 indicates that the central regions of these objects should be gravitationally bound. If the HI were dense enough pre-encounter then CO would form and be routinely detected beyond R_{25} (the optical radius) in galactic disks, like HI – it is not [17] [20] [21] [23]. While it was clear that TDGs are kinematically decoupled from their parent galaxies, prior to these data, the evidence that TDGs were bound was morphological – the accumulation of matter at the tips of the tidal tails and the presence of star forming regions. Although higher angular resolution is necessary, this conclusion provides firmer ground for the calculation of the dynamical mass, which relies on the assumption that the object is gravitationally bound and in equilibrium, and thus for the determination of dark matter which by definition is detected as discrepancy between the velocities expected based on the mass of what we see directly and those observed.

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	A105S	A245N
RA(J2000)	11 11 13.5	09 45 44.1
Dec(J2000)	+28 41 20	-14 17 28
HI velocity (LSR)	$cz = 8890\,\mathrm{km\,s^{-1}}$	$cz = 2175\,\mathrm{km\,s^{-1}}$
adopted distance	115 Mpc	31 Mpc
$L_{\mathrm{H}\alpha}$	$1-2\times10^{40}\,\mathrm{erg\,s^{-1}}$	$7\times10^{39}\,\mathrm{erg\,s^{-1}}$
$\mathrm{M_B}$, $\mathrm{L_B/L_{B\odot}}$	-16.9, 9×10^{8}	-17.25, 1.2×10^{9}
B − V	0.3	0.55
M_{HI}	$5\times10^{8}\,\mathrm{M_\odot}$	$9\times10^{8}\,\mathrm{M_\odot}$
$M_{\mathrm{H_2}}(\mathrm{M_\odot})$	$\geq 2.2\times10^{8}$	$\geq 1.4\times10^{8}$

Table 1: Properties of the Arp 105 and Arp 245 Tidal Dwarf Galaxies. The data are from [2] [3] for A105S and [14] for A245N. Position is (0,0) of CO map and velocity is zero of spectra (Fig. 3). $\mathrm{M_B}$ and $\mathrm{L_B}$ include a correction for galactic absorption of 0.3 magnitudes for A245N. A105S is at high galactic latitude so no correction is applied. The molecular gas mass is estimated using a $N(\mathrm{H_2})/I_{\mathrm{CO}}$ factor of 2 $\times10^{20}\,\mathrm{K\,km\,s^{-1}cm^{-2}}$ and likely represents a lower limit because weaker, undetected, CO emission may be present at other positions. We have included the mass of Helium in the molecular clouds. Relative to the velocities of the TDGs, the spiral and elliptical in the Arp 105 system have velocities of -130 and -400 km/s. In Arp 245, the velocities of the spirals NGC 2992 and NGC 2993 are 155 and 245 km/s with respect to the TDG.

Source	offset (δRA,δDec)	I_{CO} K km/s	rms mK	vel. km/s	ΔV_{fwhm} km/s
A105S	(0,0)	0.3±.05	2.5	19±6	38±10
		0.2±.05	3.5	16±5	25±10
A105S	(10,0)	0.1±.05	3	59±6	19±10
A105S	(-10,0)	0.15±.05	2.8	-4±5	22±13
A105S	other	0.15±.05	2.5	15±6	15±8
A245N	(0,0)	1.3 ± .1	4.9	-32±4	48±10
		2.0 ± .5	18	-32±10	66±20
A245N	(3,14)	0.6 ± .15	7	-33±10	47±15
A245N	(0,-10)	0.9 ± .15	7.6	-27±7	44±14
A245N	(0,-20)	0.5 ± .2	9.5	-27±12	32±15

Table 2: Molecular gas in Tidal Dwarf Galaxies. The CO observations presented here provide the first detections of molecular gas in TDGs. The offset is in arcseconds with respect to the position given in Table 1 and the red circle in Figures 1 and 2. I_{CO} is the flux of the CO line expressed in Kelvin km/s. The lines without source and offset are the CO(2–1) observations of the preceding source and position. Noise levels (rms) are given for channel widths of 2 MHz in the CO(1–0) line and 2.5 MHz in the CO(2–1) line. The velocity of the line center is with respect to the HI velocity given in Table 1. Note that the "detections" of the off-center A105S positions are uncertain so the velocities and line widths may be meaningless. The spectra for each position were averaged, a continuum level was then subtracted such that the average flux outside the line window is zero, and resulting spectra were smoothed to yield the results presented in Fig. 3 and Table 2. No baselines other than the continuum level are subtracted from the data. The A105S "other" position represents the average of the spectra for the (0,5) (0,-5) and (0,-10) positions. Taken individually, these points were not detected and yield 3σ limits of $I_{CO} \lesssim 0.3$K km/s. The CO emission from A105S is consistent with a near-punctual source, much like for the optical and HI. The angular resolutions are respectively 22″ and 11″; beam efficiencies are 0.72 and 0.48.

Figure 1: The Southern Tidal Dwarf Galaxy (blow-up) in the interacting system Arp 105 (NGC 3561 [24]; "the Guitar"). HI emission contours are superposed on a blow-up of a V band image of A105S [3]. The frame is $4.4'$ x $5.9'$; North is up and East to the left. Red circle is (0,0) position of CO observations and represents the FWHM ($22''$) of the CO(1–0) beam. The Arp 105 system [2] [3] is an interaction between a spiral and an elliptical which has generated an HI-rich extended TDG at the end of the Northern tidal tail and a more compact TDG at the tip of the Southern tail from the spiral. Arp 105 South (A105S) contains roughly 5 10^8 $M_\odot$ of HI and strong $H\alpha$ emission, corresponding to a star formation rate of $\sim 0.2 M_\odot$/yr. Nonetheless, stellar synthesis models [25] of A105S indicate that the stellar mass is dominated by the old spiral disk population while the luminosity comes in majority from stars formed *in situ*.

Figure 2: The Tidal Dwarf Galaxy (blow-up) in the interacting system Arp 245 (NGC 2992/3 [24]). HI emission contours are superposed on a blow-up of a V band image of A105S [14]. The frame is $5.8'$ x $7.4'$; North is up and East to the left. Red circle is (0,0) position of CO observations and represents the FWHM ($22''$) of the CO(1–0) beam. Arp 245 is an interaction between two spirals. The TDG, A245N, has been formed in the tidal tail which stems from NGC 2992 and contains nearly twice as much HI as A105S but slightly weaker $H\alpha$ emission. The old stellar population is more prominent in A245N than in A105S [14]. The physical size and total HI mass of Arp 245 are smaller than in Arp 105.

Figure 3: CO(1–0) and HI spectra of the (0,0) position of A105S (left) and A245N (right). The velocities and line widths of the CO and HI emission are very similar. Towards the very compact TDG A105S, the CO emission is not resolved. The CO emission in A245N is extended with detections in *at least* 3 of 4 observed points. The $H\alpha$ emission in A245N [14] decreases substantially towards the (0,-10) offset position while the HI [14] and CO (see Table 2) are still strong. In contrast, the $H\alpha$ emission towards the (3,14) position is comparable to the center whereas the CO and HI have decreased significantly. The temperature scale (main beam) is in milliKelvins and velocities in km/s. HI intensity is in arbitrary units.