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Star Formation in Tidal Dwarf Galaxies

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Abstract.   Tidal Dwarf Galaxies (TDGs) are objects presently forming from gas that has been expelled from their parent galaxies during an interaction. We searched for CO emission in a sample of 11 TDGs, of which 8 were detected. The CO is found at the peak of the HI observations and has the same line velocity and width, indicating that the molecular gas is forming in situ instead of being torn from the parent galaxies. The presence of Hα emission furthermore shows that stars are forming from this molecular gas. In order to investigate star formation in TDGs further, we compared their molecular gas content and star formation rate (SFR), traced by Hα, to those of spiral galaxies and classical dwarfs. The major difference between TDGs and classical dwarfs is the lower metallicity of the latter. The star formation efficiency (SFR per molecular gas mass) of TDGs lies in the range typical of spiral galaxies indicating that star formation is proceeding in a normal fashion from molecular gas.

1.   What are Tidal Dwarf Galaxies?

TDGs are small galaxies that are currently in the process of formation. They are forming from material ejected from the disks of spiral galaxies through galactic collisions. Their properties are very similar to classical dwarf irregulars and blue compact dwarf galaxies, except for their metallicities, which are higher and lie in a narrow range of 12+log(O/H)$\approx$ 8.4 − 8.6 (Duc et al. 2000). These metallicities are typical of the material found in the outer spiral disks of the interacting galaxies and which is most easily lost to form TDGs.

TDGs are interesting objects because they allow us to observe the process of galaxy formation, similar to what occurred in the early universe, but in local objects at high sensitivity and resolution. Their age can be constrained via numerical simulations of the collision. Their discovery has raised the question how large a fraction of the current dwarf galaxy population could have formed as TDGs, and how these could be distinguished from the population of what are believed to be regular field dwarf galaxies. A possible way to distinguish between a field or tidal dwarf galaxy is via their dark matter content. According to simulations, TDGs should contain no dark matter (Barnes & Hernquist 1992), whereas most classical dwarfs have a high dark matter fraction (see Hunter et al. 2000).

2.   CO in Tidal Dwarf Galaxies

TDGs have a high SFR. Their metallicities are not as low as in many classical dwarfs. They possess high atomic hydrogen column densities. Therefore, large amounts of molecular gas should be present and, assuming that the conversion factor between the CO emission and molecular gas mass is similar to the Galactic value, it should be detectable. Surprisingly, first attempts to detect CO in Arp 105 (Duc & Mirabel 1994) and the Antennae (Smith & Higdon 1994) failed.

Between June 1999 and September 2000 we observed a sample of 9 TDGs with the IRAM 30m telescope in CO(1–0) and CO(2–1). Two further TDGs, NGC 5291N and NGC 5291S, were observed with the SEST telescope in the same transitions. The main motivation for these observations was (i) to find out whether molecular gas can be detected in TDGs or whether their molecular gas content is much lower than would be expected from simple estimates, (ii) to study the formation of molecular gas from atomic gas, (iii) and to to check whether star formation is going on in the same way as in other galaxies. The details of the observations and a broader discussion of the results can be found in Braine et al. (2000, 2001).

We searched for CO at the peaks of the H I emission and detected 8 of the objects. In Table 1 the observed TDGs, the measured molecular mass and further data are listed.

3.   What is the origin of the molecular gas?

At the scales sampled by the CO and H I observations, 1 − 10 kpc, the CO is detected at the H I column density peak and shares the same kinematics in terms of line widths and velocity. This is very different from what is found in

Table 1.   Data for the sample of TDGs

Source/System	M_{mol}[a] 10^8 $M_\odot$	M_{HI}[b] 10^8 $M_\odot$	$L_{H\alpha}$ 10^{39} erg s^{-1}	metallicity $12+\log(O/H)$
UGC957/NGC 520	$\lesssim 0.06$	0.27	–	–
NGC2782W/NGC 2782	$\lesssim 0.12$	1.5	–	–
Arp245N/Arp 245	0.64^c	2.7	7.4	8.6
Arp105S/Arp 105	2.2	4.1	$10 - 20$	8.4
NGC4038W/Antennae	0.03^d	0.17^d	1.7	8.4
NGC4676N/NGC 4676	1.1	16	$10 - 20$	–
NGC5291N/NGC 5291	1.9	24	9.3	8.4
NGC5291S/NGC 5291	2.9	14	5.6	8.5
IC1182E/IC 1182	$\lesssim 1.0$	23	–	8.4
NGC7319E/Stephan's Qu.	4.5	8.7	13.6	–
NGC7252W/NGC 7252	0.36^d	0.78	1.0	8.6

[a] The molecular gas mass was calculated using a conversion factor of $N(H_2)/I_{CO} = 2 \times 10^{20}$ cm^{-2}(K km s^{-1})$^{-1}$ and assuming a helium mass fraction of 0.27. This yields $M_{mol} = 1.073 \times 10^4 (D/Mpc)^2 (S_{CO}/Jy\,km\,s^{-1}) M_\odot$

[b] Atomic (H I and He) gas mass within the same area as CO.

[c] extended source, molecular and atomic gas masses in central beam only

[d] Derived from CO(2–1) line (CO(1–0) was not detected) assuming a ratio of the brightness temperatures of CO(2–1)/CO(1–0) of 0.75 and assuming that the CO emission fills the CO(2–1) beam. M_{mol} should be viewed as an upper limit, because the CO(1–0) emission could be optically thin or even more concentrated.

spiral galaxies, where CO is only detected within the optical radius whereas H I is much more broadly distributed (e.g., NGC 891, García–Burillo 1992). This suggests that the molecular gas that we are observing in the TDGs is *not* torn from the parent galaxies but formed *in situ*. In the following we will give some more arguments why we think this is so and present counterarguments why we consider it unlikely that the molecular gas has been torn as such from the parent galaxies, together with the atomic gas.

First of all, based on the standard dust model (Mathis, Rumpl, & Nordsieck 1977), the timescale to transform, say, 20% of H I into H$_2$ is of order $t_{20\%} = 10^7/n_{HI}$ yr. At H I volume densities of typically > 1 atom cm^{-3} this is much shorter than the timescale of the interaction which is of order 10^8 yr. Secondly, if the molecular gas were torn from the outer disks of the interacting galaxies we need to assume that there exist large quantities of H$_2$ beyond the optical radius of a typical spiral galaxy and that these are hidden from view, either because: (i) the gas has too low a density, (ii) it is too cold, or (iii) its metallicity is too low. All three possibilities seem unlikely:

(i) If the molecular gas had very low density, CO could be dissociated. However, CO becomes self-shielding at CO column densities of a few 10^{14} cm^{-2}, corresponding to typical H$_2$ column densities of several 10^{20} cm^{-2}. Absorption measurements towards stars indicate that at total (atomic and molecular) hydrogen column densities of order a few 10^{20} cm^{-2} the molecular hydrogen fraction is very small (Federman et al. 1979). Thus, if the gas is dense enough to form molecular clouds, it is also dense enough to have a normal CO content.
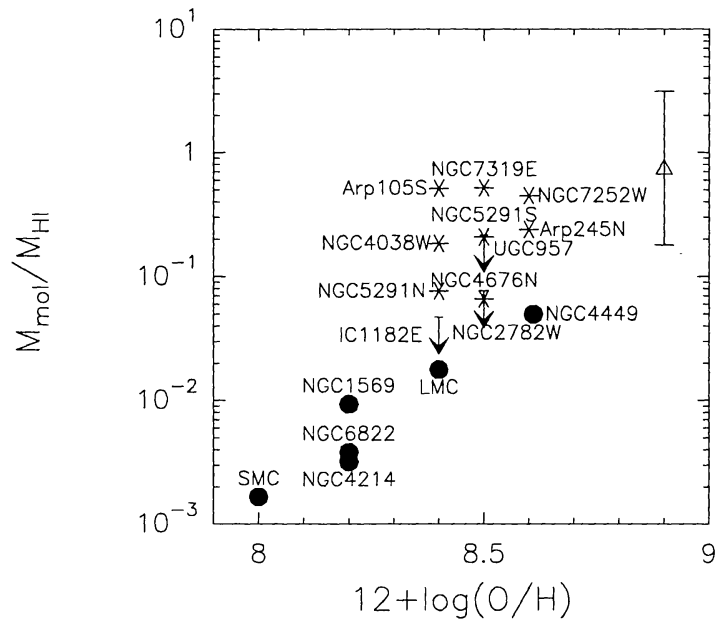
Figure 1. The molecular gas fraction versus metallicity. For TDGs with no measured metallicity (see Tab. 1) we have tentatively assumed 12+log(O/H) = 8.5. The stars denote TDGs, filled circles classical dwarfs and the triangle the median value of the spiral galaxies from the sample of Kennicutt (1998), the errorbar showing the standard deviation around the median of that sample.

(ii) Liszt & Lucas (1998 and references therein) observed Galactic CO in emission and in absorption towards quasars. In virtually all cases where absorption was measured, they also found CO emission. This shows that there is no substantial population of molecular clouds in the Galaxy where the CO is present but too cold to be detected in emission.

(iii) Is it possible that TDGs are formed from molecular gas of the very outer regions of spirals where low metallicity inhibits any CO emission? If this were the case, star formation in TDGs would have had to enrich the gas to its present metallicity. We think that this scenario is unlikely because firstly, it does not explain the common metallicity of TDGs. Secondly, star formation is occurring in many dwarf galaxies of sizes comparable to TDGs (e.g., Taylor et al. 1998) at rates at least as high as in our TDG sample. Were star formation capable of considerably enriching the gas, dwarf galaxies would not have such low metallicities. Finally, it is hard to see how molecular gas supposedly coming from the parent galaxies can survive the star formation necessary to increase its metallicity.

Thus we conclude that if large quantities of molecular gas had been present in the outer parts of spiral galaxies – from where the material forming TDGs comes from – it should be observable. This fact together with the spatial and dynamical coincidence of atomic and molecular gas suggests that we are seeing molecular gas formation. The CO emission furthermore coincides with the position of Hα emission tracing star formation. Thus, we are witnessing the entire process of star formation: The formation of molecular from atomic gas and the subsequent star formation.
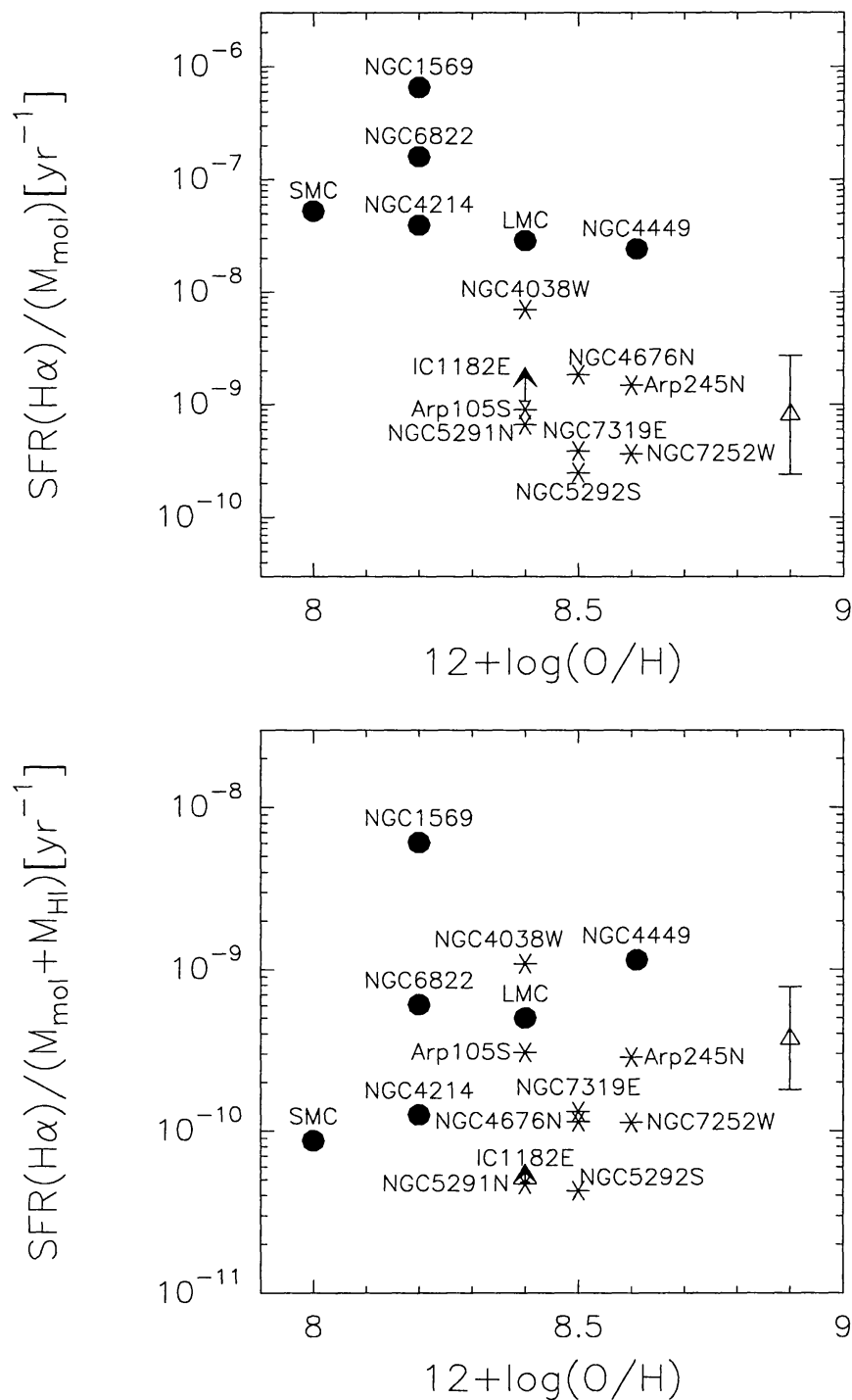
Figure 2. Left: The SFR, traced by $H\alpha$ emission, divided by the molecular gas mass. – Right: The SFR divided by the total (molecular and atomic) gas mass. The different symbols describe the three samples as explained in Fig. 1.

4. Star formation in TDGs, classical dwarfs and spirals

Is star formation proceeding in the same way in TDGs as in classical dwarfs and in spiral galaxies? In order to discuss this question we compare some properties of our TDG sample to samples of classical dwarfs and spirals. The data for spirals are taken from Kennicutt (1998). We calculated median values and dispersions from his Table 1 and assumed a metallicity of 12+log(O/H) =8.9 for this average spiral. Details of the data of the classical dwarf sample are given in Braine et al. (2001), except for the H I data which are taken from Stil & Israel (priv. communication, NGC 1569), Melisse & Israel (1994, NGC 4214), Israel et al. (1996, NGC 6822), Hunter & Thronson (1996, NGC 4449), Cohen et al. (1988, LMC) and Rubio et al. (1991, SMC). The H I masses refer to the area in which molecular gas was detected. The molecular gas mass for all objects was calculated or scaled to the same conversion factor given in Table 1.

In Fig. 1 the molecular gas fraction versus metallicity is shown. The molecular gas fractions of TDGs are higher than for classical dwarfs and lie within or only slightly below the typical range of spiral galaxies. There seems to be a trend of $M_{mol}/M_{H I}$ with metallicity, although with a large scatter. This trend most likely reflects a decrease of the CO-molecular-gas-mass conversion factor with decreasing metallicity as indicated by observational (e.g., Wilson 1995) and theoretical (Maloney & Black 1988) studies.

This means that the molecular gas in TDGs is easier to detect than in classical dwarfs due to the higher metallicity of TDGs. Whereas classical dwarfs follow a luminosity-metallicity relation, the metallicities of TDGs lie all in a narrow range between 8.4 and 8.6 (Duc et al. 2000). As a consequence we are able to observe molecular gas in TDGs of lower luminosities than classical dwarfs. In the latter objects no CO is detected for metallicities lower than 12+log(O/H) = 7.9 (Taylor et al. 1998), corresponding to galaxies fainter than $M_B \approx -15$ mag (Skillman et al. 1989). TDGs of comparable luminosity can be observed in CO, as the detections of NGC 7252W, NGC 4038S and NGC 7319E, all with blue magnitudes between −14 and −15 mag, show.

A widely used parameter to study star formation is the star formation efficiency (SFE) which is defined as SFR per molecular mass. Here, we use the Hα luminosity as a tracer of the SFR as: SFR = $5 \times 10^{-8}(L_{H\alpha}/L_\odot)M_\odot \text{yr}^{-1}$ (Hunter & Gallagher 1986). In Fig. 2 (left) we show the SFE versus metallicity. There is a clear difference between TDGs and classical dwarfs: Whereas the SFE of most TDGs falls in the same range as for spirals, classical dwarfs possess a higher ratio. This difference persists even when considering a possible underestimate of up to 50% of the $L_{H\alpha}$ in some TDGs for which only long-slit measurements are available. Most likely the apparently high SFE of classical dwarfs is caused by an underestimate of the molecular gas due to their low metallicities. This assumption is supported by Fig. 2 (right) where we plot the SFR divided by the *total* gas mass. In this case the whole sample falls in a much narrower range. The SFR normalized to the *total* gas mass of some TDGs is somewhat lower than the range of values of the spiral galaxy sample. This could be due to an overestimate of their H I content due to insufficient resolution of the data. Alternatively, it could imply that TDGs possess a reservoir of atomic gas that is not used (yet) for star formation, reflecting the fact that TDGs are in the process of formation and the star formation is just starting.
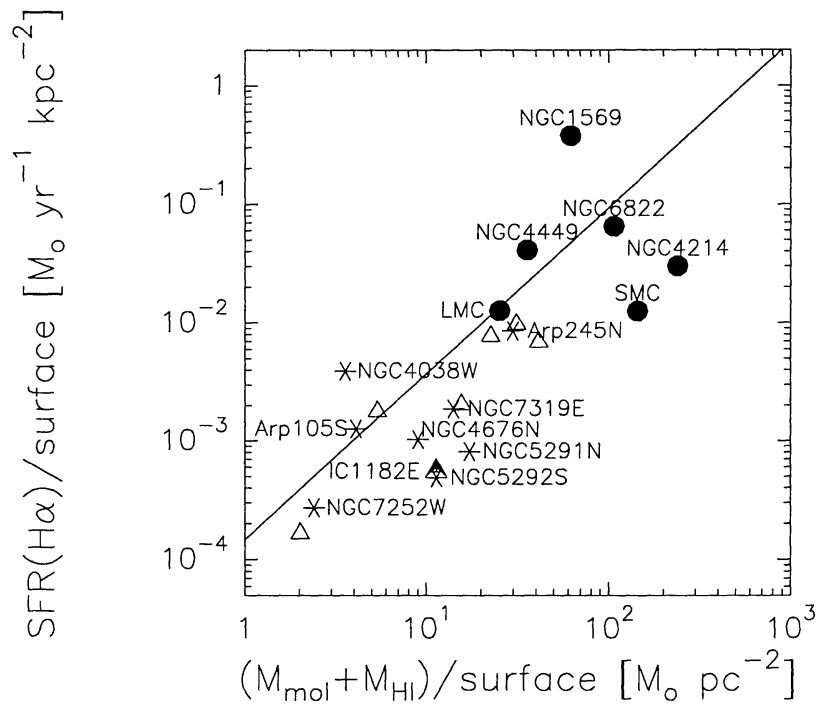
Figure 3.   The SFR per surface area as a function of the gas mass surface density. The solid line gives the best fit derived by Kennicutt (1998) for a large sample of galaxies of different types (ranging from dwarfs to starburst galaxies). The triangles are some galaxies from Kennicutt's sample.

Schmidt (1959) has suggested a relation between the SFR per surface area, Σ_{SFR} and the gas mass surface density, σ_{gas}, $\Sigma_{SFR} \propto \sigma_{gas}^{\alpha}$. Kennicutt (1998) showed that indeed a tight correlation between these two quantities holds for different types of galaxies and spans many orders of magnitude. In Fig. 3 we show this relation for our sample. We include the best-fit line of the Kennicutt sample. The entire sample follow the same relation, indicating that star formation proceeds in a normal fashion.

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Discussion

Larson: What can you say about the lifetimes of tidal dwarfs? I would have guessed that most of them would be loosely bound or even unbound and not survive for long. Because if they originate in the same way as massive star-forming complexes in the outskirts of spiral galaxies, these complexes are generally not bound, or don't stay bound for long. So I wonder how long tidal dwarfs formed this way might survive.

Lisenfeld: At the moment the TDGs are bound. We believe that the fact we see the formation of molecular gas supports this idea, because it is hard to imagine the concentration of gas necessary for the molecular gas formation in an unbound medium. It is hard to say how long these objects will survive. This depends, among other things, on their distance to their parent galaxies.

Hunter: Since the interaction that creates a tidal dwarf pulls out the ISM of spiral galaxies, would another diagnostic of an older tidal dwarf be that it is dustier than other irregulars?

Lisenfeld: Since the metallicity of tidal dwarf galaxies is higher than that of classical dwarfs, also the dust-to-gas mass ratio should be higher. In any case, dust is needed for the formation of molecular gas, so we expect that dust should have been expelled from the parent galaxies together with the HI. But the fluxes expected for the dust emission are very low, at maximum just detectable at submillimeter wavelengths.