Molecular Gas and Star Formation in Tidal Dwarf Galaxies

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Abstract

Tidal Dwarf Galaxies (TDGs) are objects presently forming from gas which has been expelled from their parent galaxies during an interaction. We observed the CO emission of 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 which 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 field dwarf galaxies. A possible way to distinguish between a field and a 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).

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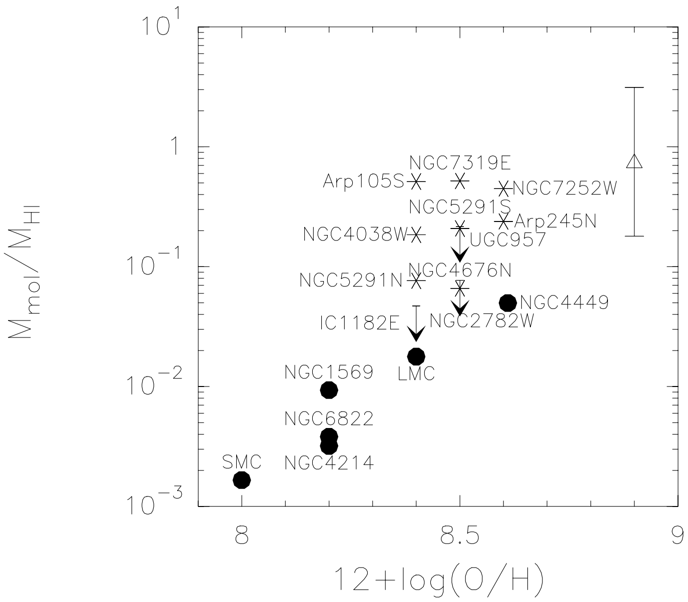

Figure 1: The molecular gas fraction versus metallicity. For TDGs with no measured metallicity (UGC 597, NGC2782W, NGC4676N, NGC7319E) we have tentatively assumed 12+log(O/H) = 8.5. The stars denote TDGs, filled circles classical dwarfs and the triangle the median value of the spiral galaxies from the sample of Kennicutt (1998), the errorbar showing the standard deviation around the median of that sample.

2 CO in Tidal Dwarf Galaxies

TDGs have a high SFR, their metallicities are not as low as in many classical dwarfs and 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 motivations for these observations were (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 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 HI emission and detected 8 of the objects.

3 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). The HI masses refer to the area in which molecular gas was detected. The molecular gas

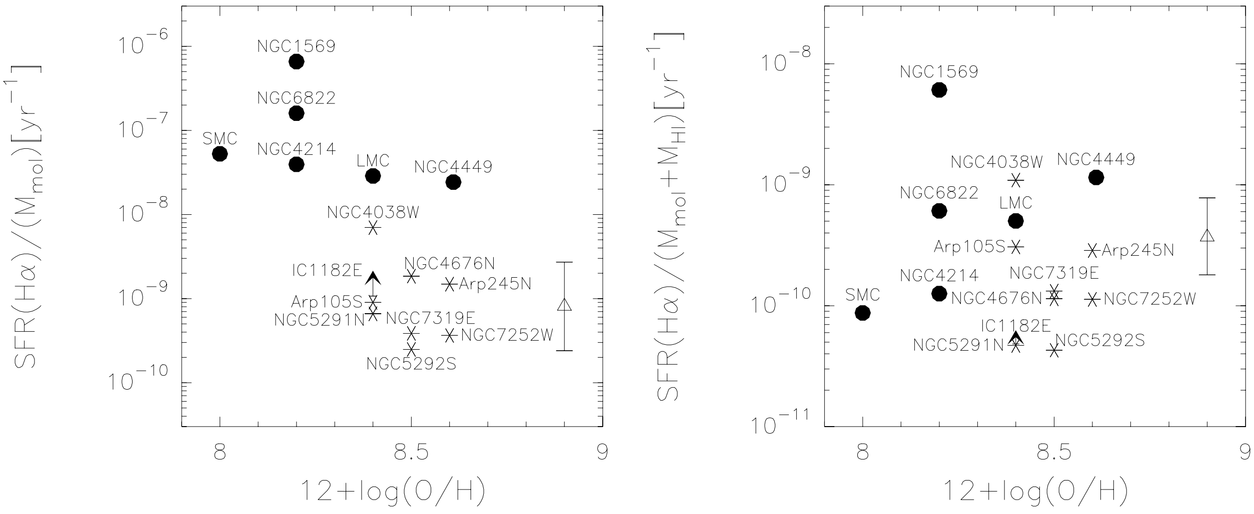

Figure 2: **Left**: The SFR, traced by Hα emission, devided by the molecular gas mass. **Right:** The SFR devided by the total (molecular and atomic) gas mass. The different symbols describe the three samples as explained in Fig. 1.

mass for all objects was calculated using the same conversion factor.

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 $M_{\rm mol}/M_{\rm HI}$ 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) = 8.0 (Taylor et al. 1998), corresponding to galaxies fainter than $M_{\rm B} \approx -15$ mag (Skillman et al. 1989). TDGs of comparable luminosity can be observed in CO, as the detections of NGC 7252W, NGC4038S and NGC7319E, all with blue magnitudes between -14 and -15, 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 $= 5 \times 10^{-8}(L_{\rm H\alpha}/L_{\odot})M_{\odot}{\rm yr}^{-1}$ (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 $L_{\rm H\alpha}$ 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 devided 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 HI 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.

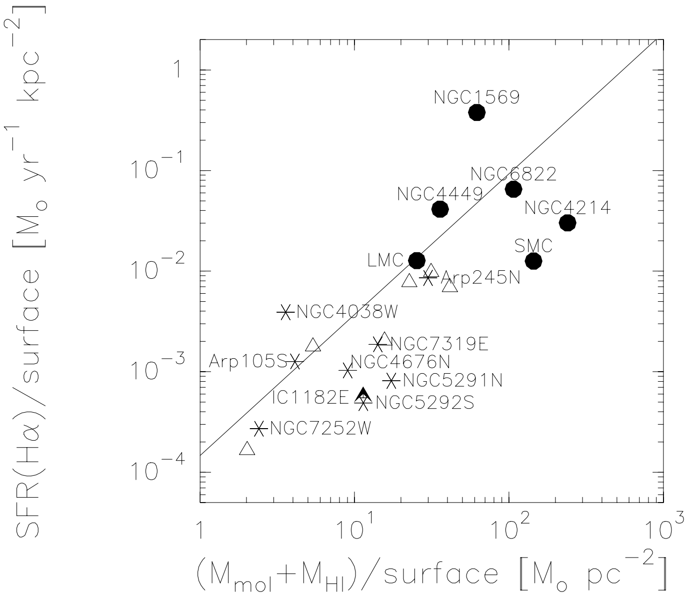

Figure 3: The SFR per surface area as a function of the gas mass surface density. The solid line gives the best fit derived by Kennicutt (1998) for a large sample of galaxies of different types (ranging from dwarfs to starburst galaxies). The triangles are some galaxies from Kennicutt's sample.

Schmidt (1959) has suggested a relation between the SFR per surface area, $\Sigma_{\rm SFR}$ and the gas mass surface density, $\sigma_{\rm gas}$, $\Sigma_{\rm SFR} \propto \sigma_{\rm gas}^{\alpha}$. 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.

In summary, tidal dwarf galaxies are something of a hybrid between classical dwarf galaxies and (the outskirts of) spiral galaxies. Morphologically they resemble classical dwarfs. Their metallicity, however, is more like that of the outer parts of spiral galaxies. An important characteristic which remains to be determined is to which extent TDGs are gravitationally distinct entities, and what fraction, if any, of Dark Matter is associated with these objects.

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