Molecular gas in Tidal Dwarf Galaxies: Exploring the conditions for star formation

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Abstract. Tidal Dwarf Galaxies (TDGs), produced from material expelled in galactic interactions, are well–suited to test the laws of star formation (SF) due to their simple structure, high metallicity – making CO a reliable tracer of the molecular gas content – and recent SF. Here, we study the conditions for the onset of SF and for the rate at which SF proceeds once above a threshold in a small sample of TDGs. We use data for the gas (atomic and molecular) surface density and SF rate per area to test the laws of SF found for spiral and dwarf galaxies in this more extreme environment. We find in general a good agreement with the Schmidt law found for the total gas [17] and for the molecular gas [1] but note that higher resolution CO observations are necessary to clarify some possible discrepancies. We find, down to a scale of ~1 kpc, in general a good agreement between the peaks of SF and of the molecular gas, but also find in some objects surprisingly large quantities of molecular gas at places where no SF is occuring. A high column density of molecular gas is therefore not a sufficient condition for the onset of SF. We find that the kinematical properties of the gas are also relevant: in two objects our observations showed that SF only occured in regions with a narrow line width.

1. Introduction

A major challenge in astrophysics is understanding the process of star formation (SF) in galaxies and in particular to find out (i) what determines the threshold for star formation, i.e., what are the sufficient and necessary conditions for SF to take place and (ii) what determines, once above this threshold, the rate of SF. This knowledge is not only useful in itself, but forms a crucial ingredient for the modeling of galaxy formation and evolution (e.g., Schaye & Dalla Vecchia [28]).

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 those of 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)≈ 8.4 − 8.6 [8]. 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 well suited to test the laws of SF because of various reasons: In the same way as "classical" dwarf galaxies (i.e., dwarf galaxies not obviously formed from an interaction) the lack of differential rotation and, more importantly, the absence of prominent density waves make shear and centrifugal forces less important and reduce in this way the number of parameters that affect SF. Furthermore, TDGs lack an old stellar population, because they are made almost entirely from a gaseous medium with none or only few old stars coming from the parent galaxies, so that their

gravitational potential is largely dominated by the gas distribution alone. Additionally, an advantage of TDGs with respect to classical dwarf galaxies is their higher metallicity which makes CO a good tracer of the molecular gas and thus allows us to directly study the relation between molecular gas and SF.

The goal of this contribution is to discuss the relation between SF and molecular gas in TDGs. To this aim, the existing observations and their basic results are reviewed and compared to different theories describing the laws of SF and conditions for the onset of SF.

2. Observations of the molecular gas

The first detection of molecular gas in a sample of TDGs [4, 5] revealed in all objects a good spatial overlap between the areas where molecular gas is detected, the sites of SF and the peak of the atomic gas. Furthermore, the kinematical properties of the atomic and molecular gas are identical, i.e., both lines show the same central velocity and line width.

These single–dish observations were taken with only a modest spatial resolution (mostly about 22″, corresponding to a linear resolution between 2 and 14 kpc at the distances of the objects, between 22 and 135 Mpc). Nevertheless, they allowed us to determine the molecular-to-atomic gas mass ratio and the molecular star formation efficieny (SFE, defined here as the SF rate devided by the molecular gas mass) and compare them to those of spiral galaxies. The molecular gas mass in TDGs was calculated adopting a Galactic conversion factor ($N_{H2}/I_{CO} = 2 \times 10^{20}$ cm^{-2}(K km s^{-1})$^{-1}$), the same factor adopted in the present contribution. Contrary to classical dwarf galaxies, TDGs show both a molecular gas fraction and a SFE in the range of spiral galaxies [5, 20]. The authors concluded that (i) the CO-to-H$_2$ conversion factor is indeed similar to the Galactic value and not, as in classical dwarf galaxies, much lower and (ii) SF proceeds in a normal way in TDGs, similar to that occurring in spiral galaxies.

Since then, a few objects have been observed at higher spatial resolution. Interferometric observations have been carried out in two objects, the northern TDG, Arp 245N, in the interacting system NGC 2992/3 (Arp 245) [7] and the TDG SQ B in Stephan's Quintett [21]. These observations confirmed at a higher spatial resolution that the peak of the molecular gas coincides reasonably well with recent SF, traced by Hα, although at the highest spatial resolution, in Arp 245N a marginally resolved displacement of about 3-4″(400 − 600 pc) was found between both peaks. The comparison of the total flux of the interferometric and single-dish observations showed that a large fraction (25% for Arp 245N and 50% for SQ B) of the flux is missing in the interferometric observations, indicating the presence of a considerable amount of smoothly distributed molecular gas.

Wide-spread molecular gas was also found in two nearby objects where the single-dish observations provided enough linear resolution to create maps. One object is an old TDG in the Virgo Cluster, VCC 2062 [9] and the other is a potential TDG in the interacting system Arp 94, J1023+1952 [22]. In both objects, the star–forming region sits within a large HI cloud. Surprisingly, molecular gas was not only found to coincide with SF regions, but also, in large quantities, at places where no SF is ocurring. The distribution of the molecular gas follows, although not at a strictly constant ratio, that of the atomic gas and the kinematical properties of HI and H$_2$ are similar. Neither the column density of the molecular nor the column density of the total (atomic plus molecular) gas seems to be a relevant parameter to explain why SF is present in only one region of the gas clouds, and in particular a lack of molecular gas is not the reason for the absence of SF over a large extent of the cloud. A similar result was obtained by [23] who found in a survey of tidal tails that a high column density ($\log N_{HI} > 20.6$ cm^{-2}) is a necessary but not sufficient condition for SF to take place.

We found, however, a kinematical difference in the gas properties: the line width in the SF region is narrower (FWHM ∼ 30-70 km s^{-1} for J1023+1952 and FWHM ∼ 20 km s^{-1} for VCC 2062) than in

the region without SF where the line width is about a factor of 2 higher. This indicates that dynamically cold gas is a necessary condition for SF to take place.

In summary, we found the following common features in the properties of the molecular gas and SF in TDGs:

- There is a close relation between atomic and molecular gas, both spatially and kinematically. The molecular-to-atomic gas mass ratio is similar to that of spiral galaxies.
- In SF regions, molecular gas is present and the SFE in TDGs is similar to that of spiral galaxies.
- The distribution of the molecular gas is *not* limited to the SF region, and abundant molecular gas was found over a large extent of the HI distribution.
- The column density of the molecular gas and of the total gas is not the key parameter for the presence of SF. The kinematical properties of the gas play an important role as well in the sense that SF only takes place in dynamically cold gas.

3. Testing the laws of star formation

In this section we compare the observations to existing theories for SF. We start with a review of the most common theories.

3.1. Theories of star formation

In a classical paper, [31] derived a prescription for the stability of a gas disk against collapse and star formation, taking into account gravitation on one hand and internal pressure and galactic rotation as stabilizing processes on the other. This Toomre–criterion has shown to be a reasonably good predictor of the SF threshold (e.g., Kennicutt [17]), especially when the stellar mass component is properly taken into account to describe the gravitational field [16]. Since in dwarf galaxies differential rotation is not very important, shear has been suggested as an alternative mechanism to prevent gravitational collapse [10, 11, 12] and has been found to be a better description for the onset of SF in dwarf galaxies [15]. However, SF has also been found in regions which are globally well below the SF threshold [14, 6]. This is explained in general terms by the fact that the Toomre parameter does not represent a strict lower threshold in the sense that local parameters like the magnetic field, turbulence and variations in the local velocity dispersion can allow SF to take place even below the global threshold [27]. An alternative explanation is that the mass of star clusters in the outer disk environment is decreasing, leading to an reduced Hα emission for a given SF rate (SFR) [26]. A strict lower limit for SF is expected to be set by the minimum density providing the necessary pressure to maintain cool atomic gas [13, 28]. This lower limit is expected to be around 3 - 10 $M_\odot\,pc^{-2}$ but will depend on parameters like the radiation field and the metallicity. The exact relation between the threshold and these parameters is, however, still a matter of debate.

Once supercritical conditions are reached and SF starts, its rate is expected to depend on the gas density and the characteristic time scale for cloud collapse. Together this leads to the prediction by Schmidt [29], who suggested that the SFR is proportional to the gas volume density to the power n, where $n = 1.5$ (note that for a constant scaleheight gas disk, the same relation holds between the SFR density in the disk and gas surface density). Several studies have found n to lie between 1 and 2. [17] determined n to be close to 1.40 ± 0.15 over 5 orders of magnitude. The precise value of n depends on many factors which complicate its interpretation. For example, although one would expect total, i.e., atomic plus molecular hydrogen, gas surface density to drive the SFR, Wong & Blitz [32] argue that in fact it is only the H_2 which is involved. This is now being confirmed on a much larger sample using THINGS (The HI Nearby Galaxy Survey) data [1, 19] .

Table 1. SFR surface density and gas surface densities

Name	Distance [Mpc]	resolution[a] [''/kpc]	Σ_{HI} [M$_\odot$pc^{-2}]	Σ_{H2}	Σ_{SFR} [10^{-3}M$_\odot$yr^{-1}kpc^{-2}]	$\Sigma_{H2}/\Sigma_{HI+H2}$	SFE(H$_2$)[b] [10^{-10}yr^{-1}]
VCC 2062	17	22''/1.8kpc	7.1	2.7	0.2 – 1.1	0.28	0.9 – 4.1
Arp245N	31	~ 4''/0.6 kpc	18.2[c]	10.0	24	0.35	24
J1023+1952	20.4	22''/2.2kpc	9.5	4.7	4.2 – 8.4	0.33	9 –18
SQ B	85	~ 4''/1.6kpc	5.5[c]	12	17	0.68	14

[a] Resolution of the CO. The resolution of the HI data is about 20'' for all objects.
[b] The molecular star formation efficiency, SFE(H$_2$), defined as the SFR per molecular gas mass. The range of values given for VCC2062 and J1023+1952 is due to different areas adopted for the size of the SF region (see Sect. 3.2).
[c] Obtained at a poorer angular resolution (~ 20'') than the CO. The peak column density could therefore be underestimated.

Different prescriptions have been proposed to explain the SFE, such as the Toomre criterion, a constant column density threshold [27], Silk's suggestion of star formation being dependent on a dynamical time scale [30], as well as the model by Blitz & Rosolowsky [2] who suggest that the transformation between atomic and molecular gas, and thus the relation between gas and SF, is solely determined by hydrostatic pressure. Additionally, large scale turbulence (i.e., the velocity dispersion between molecular clouds) might play a role. Elmegreen [13] suggests that large-scale turbulence can play a double role: it can trigger SF by compression of preexisting gas clouds, but it can also inhibit SF if the motions continously force the gas to break up to pieces that are smaller than a thermal Jean mass. Using THINGS data, Leroy et al. [19] tested a number of these prescriptions in dwarf and spiral galaxies. Of all prescriptions investigated, the model by Blitz & Rosolowsky [2] is the one which performed best throughout, although none of the other theories can be ruled out decisively, even though they are based on very different physical assumptions.

3.2. Comparison of theory and observations

In Lisenfeld et al. [20] we showed that the SFR and gas column density of the sample of TDGs observed up to that date and at a modest resolution (22''for the CO) followed the Schmidt-law found by Kennicutt [17] reasonably well. Here, we want to test this again for those objects for which in the meanwhile spatially resolved observations have become available. Additionally, we compare our data to more recent results of Leroy et al. [19] and Bigiel et al. [1], based on the THINGS survey.

We determined the SFR from the extinction corrected Hα luminosity following the prescription given in Bigiel et al. [1]

$$\text{SFR[M}_\odot\text{yr}^{-1}] = 5.3 \times 10^{-42} L_{H\alpha}[\text{erg s}^{-1}] \tag{1}$$

Kennicutt [17] used a SFR a factor 1.5 higher and we adopt his value when comparing to his data (Figure. 1, left panel). We use a CO-to-molecular gas conversion factor of $N_{H2}/I_{CO} = 2.0 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$, as in Bigiel et al. (2004) and Leroy et al. (2004), but adopt to the higher value of Kennicutt [17] of $N_{H2}/I_{CO} = 2.8 \times 10^{20}$ cm^{-2}(K km s^{-1})$^{-1}$ in Figure 1 (left panel).

In Table 1 we show the values for the molecular and atomic gas surface densities, Σ_{H2} and Σ_{HI}, respectively, and the SFR surface density, Σ_{SFR}. In the case of VCC2062 and J1023+1952 we give two values for Σ_{SFR}. The lower value is calculated by averaging the SFR over the area corresponding to the the CO beam in order to compare the data at the same angular resolution. The higher value gives the SFR averaged over the SF region only. In Figure 1 we compare these values to the Schmidt laws found
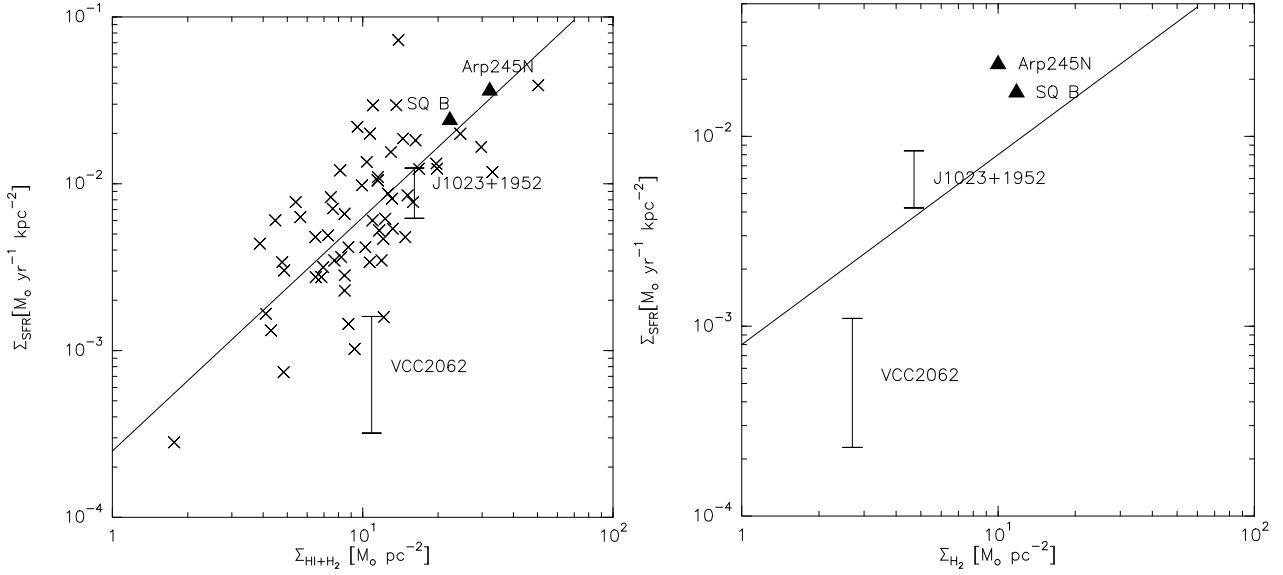
Figure 1. *Left panel:* The relation between the SFR per area and the total gas mass per area (the Schmidt law). The crosses are data for a sample of spiral galaxies from Kennicutt [17] (his Table 1) and the triangles are TDGs for which spatially resolved observations are available. The line gives the fit of Kennicutt [17] to his entire sample consisting of spiral and starburst galaxies (his eq. 4). We plotted our data in this figure after correcting it for his higher value of the SFR and for his CO-to-molecular gas conversion factor (see text). *Right panel:* The relation between the surface density of the SFR and of the molecular gas. The line gives the fit of Bigiel et al. [1] (their eq. 3) to spatially resolved data of a sample of spiral galaxies. The range of Σ_{SFR} given for VCC2062 and J1023+1952, which only have CO data at a modest resolution, is obtained by dividing the SFR by (i) the area of the SF region (upper end of the range) and (ii) by the area corresponding to the 22″ CO beam (lower end).

by Kennicutt [17] (left) and the molecular SF law found by Bigiel [1]. Most objects follow both SF laws reasonably well, even though Σ_{SFR} of Arp245N lies a factor of 2 above the RMS scatter of 0.2 dex around the fit found for the THINGs galaxies [1]. Only the data point of VCC 2062 lies well below the line, if Σ_{SFR} is averaged over the area corresponding to the 22″ resolution of the CO data. The discrepancy disappears if Σ_{SFR} is averaged over the SF region only. Thus, if the local molecular gas surface density within the SF region is the same as the observed surface density averaged over the 22″ beam, VCC 2062 follows the Bigiel et al. relation. Higher resolution CO observations are necessary to resolve this issue. A further uncertaintly comes from the use of the Hα emission as a SF tracer. Although we corrected the Hα luminosity for extinction, dust-enshrouded SF emitting very little in Hα might be missed. In VCC 2062 this might be the case: the SFR derived from the 8μm emission [3] is about a factor of 4 higher than the SFR that we derived from the Hα. Thus, the additional use of a SF tracer sensitive to dust-enshrouded SF, like the 25μm emission [18, 19, 1] is necessary to reliably trace the total SFR.

Leroy et al. [19] found that the molecular SFE is constant in spiral galaxies with an average value of $(6 \pm 3) \times 10^{-10}$ yr^{-1}. They took into account a Helium fraction of 1.38 in the gas mass. The corresponding value without He, suitable for comparison with our data, is SFE(H$_2$) = $(8 \pm 4) \times 10^{-10}$ yr^{-1}. Most of our values lie within this range, only the value for Arp 245N lies a factor of 2 above it. Leroy et al. [19] also study the SFE in dwarf galaxies. Due to their low molecular gas content, when adopting a Galactic conversion factor, they assumed that the gas is dominated by the atomic hydrogen. They found in the central regions of dwarf galaxies much higher values for the SFE than in the central regions of spiral galaxies. The authors suggested that possibly an underestimate of the molecular gas due to low metallicity could be the reason. Our results give support to this assumption

because they show that (i) molecular gas is indeed present, although generally not, as in the centers of spiral galaxies, in a dominant fraction and (ii) the molecular SFE is mostly in the same range as that of spirals.

J1023+1952 [22] and VCC 2062 [9] are particularly interesting objects to test the conditions necessary for the onset of SF because spatially resolved observations are available and both objects consist of regions with and without SF. We can thus test the previously explained criteria for the onset of SF and search for differences that can explain the presence or absence of SF.

In these two objects the total gas column density is high at all places of the gas cloud, about 10 $M_\odot$ pc^{-2} (VCC2062) and 10-20 $M_\odot$ pc^{-2} (J1023+1952), respectively, indicating that the minimum gas density to enable the presence of cool gas is most likely reached everywhere. In VCC2062, the position-velocity diagram (see Figure 6 in Duc et al. [9]) allows us to distinguish clearly between the SF and non-SF region on a kinematical basis. The SF region is characterised by narrow lines and a velocity gradient indicating that the object is gravitationally bound. In the non-SF region no velocity gradient is visible and the lines are broad, suggesting that we are seeing HI left-over from the tidal tail which is not sufficiently dense to collapse to a bound object.

In J1023+1952 we were able to estimate the values for the critical gas density according to the Toomre criterion and according to the shear criterion based on the velocity gradient of the HI gas presented in Mundell et al. [24] (their Figure 8) and assuming that the velocity gradient is due to rotation. We found for both criteria that the observed gas column density is well above the critical value both in the SF and non-SF region of the gas clouds. Thus, these criteria cannot explain why SF is taking place in one region and not in another. Mundell et al. [25] and Lisenfeld et al. [22] showed that SF in these objects is dominated by a recent episode and they found no indication of an old stellar population. Therefore the gravitational potential of old stars is not expected to play a role.

From the above we conclude that the line width is also a relevant parameter in explaining where SF occurs. The spatial resolution of the observation is 22″, corresponding to a linear scale of ~ 2 kpc, so that we do not resolve individual molecular clouds but rather observe an ensemble of clouds within the beam. The CO line width therefore does not give us information about the properties of individual molecular clouds, but rather tells tells us something about the velocity dispersion of the different molecular clouds that we observe within the beam. A broad line width indicates that the velocity dispersion among the clouds is high, i.e., it indicates large-scale turbulence. The low velocity dispersion observed in the SF region seems to be necessary for SF to happen. We can speculate that (i) the high velocity dispersion in the rest of the gas cloud inhibits SF due to more frequent and more violent cloud collisions or that (ii) the high turbulence goes in hand with a higher scale height and thus a lower volume density of the cloud distribution making collisions between them, and thus cloud collapse and ensuing SF, less likely.

4. Summary and conclusions

We reviewed observations of the molecular gas in TDGs and compared their properties (column density, line width) to the SFR in order to test, in a different environment, the laws of SF derived for spiral and dwarf galaxies. In particular, we tested the Schmidt law by comparing the column densities of the gas to the surface density of the SFR, derived from the extinction corrected Hα luminosity, in four objects where CO and HI maps were available. We compared the results of our TDGs to those of spiral and starburst galaxies [17] and of spiral galaxies from the THINGS sample [1]. We found a reasonable agreement with the spiral galaxies, but noted in the case of VCC2062 the need for higher resolution molecular gas data in order to correctly place the galaxy on the correlation. Furthermore, we noted the need for using a SF tracer not affected by extinction in order to trace also dust-enshrouded SF.

As far as the conditions for the onset of SF are concerned, we found in two objects that a high column density of molecular gas is not sufficient. The line width is an additional important parameter to be taken into account and SF only happens in those areas with narrow lines, indicating that a low velocity dispersion among the molecular clouds is necessary for SF to take place.

Acknowledgments

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