# Birth, life and survival of Tidal Dwarf Galaxies

Pierre-Alain Duc

**Abstract** Advances on the formation and survival of the so–called Tidal Dwarf Galaxies (TDGs) are reviewed. The understanding on how objects of the mass of dwarf galaxies may form in debris of galactic collisions has recently benefited from the coupling of multi-wavelength observations with numerical simulations of galaxy mergers. Nonetheless, no consensual scenario has yet emerged and as a matter of fact the very definition of TDGs remains elusive. Their real cosmological importance is also a matter of debate, their presence in our Local Group of galaxies as well. Identifying old, evolved, TDGs among the population of regular dwarf galaxies and satellites may not be straightforward. However a number of specific properties (location, dark matter and metal content) that objects of tidal origin should have are reminded here. Examples of newly discovered genuine old TDGs around a nearby elliptical galaxy are finally presented.

## 1 Introducing Tidal Dwarf Galaxies

There is yet no consensual definition of a *Tidal Dwarf Galaxy* (TDG). Let's however stick to the acronym to define it:

• *Tidal* refers to an object made of material that was tidally expelled from galaxies. The definition may be a bit enlarged and includes objects born in general in debris of galaxy-galaxy collisions: tidal tails of mergers, but also collisional rings and even gas stripped in the intergalactic medium by other processes than tidal forces. The key element is that the building material of TDGs used to belong to a larger parent galaxy and was thus pre-enriched. In practice late–type, rotating colliding galaxies generate more debris than early–type, dynamically hot galaxies. As a consequence, TDGs should mostly be produced by wet mergers involving spiral galaxies.

• *Dwarf* means that the object born in tidal tails should have the size and mass of a

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dwarf galaxy – although this is a loose criterion given the large range of sizes/masses exhibited by dwarf galaxies (from the ultra faint ones around the Milky Way to the Magellanic type objects). This specification allows to disentangle TDGs from the Super Star Clusters and other compact stellar objects that are formed as well in colliding systems.
• *Galaxy* implies that the system is kinematically decoupled from its parent galaxy and gravitationally bound. This increases its ability to survive external gravitational stirring or internal destructive processes such as stellar feedback. In other words, TDGs are not transient objects but correspond to genuine condensations of matter that have collapsed in-situ within collisional debris.

How does this definition of a TDG translate into observational properties?
• Being recycled objects, TDGs have inherited from their parents the metal content of their interstellar medium. Thus their metallicity tells about the past chemical enrichment of their parents, and is thus not correlated with their actual mass, contrary to conventional galaxies. Made out of pre-enriched material, they should have an excess of heavy elements, provided that their parents were themselves metal rich. This implies as well that their dust content and molecular gas content, as traced by CO, is higher than in regular star–forming dwarf galaxies.
• Made out of material expelled from the dark–matter poor disks of their parent galaxies, TDGs have accreted little of their dark–matter content. As a consequence, their luminous mass (stars and gas) should be close to their dynamical, total, mass, contrary to conventional dark–matter dominated galaxies (but see Section 3).

Examples of observed Tidal Dwarf Galaxies are shown in Fig. 1. On these images of colliding systems, the TDGs appear as red stains on blue ribbons, i.e. star–forming objects within gas–rich tails. The most massive of them are usually located near their tip. Several papers have exploited the rich Ultraviolet/GALEX Infrared/Spitzer databases on interacting galaxies and investigated in details how star–formation proceeds in collisional debris (e.g. [27, 25, 2]).

At this stage, it is worthwhile noting that the vast majority of the Tidal Dwarf Galaxies so far securely identified are young objects, formed in mergers that occurred less than one Gyr ago. They still exhibit the umbilical cord linking them to their parents... i.e. the tails and bridges in which they were formed have not had the time to evaporate. Once evolved, TDGs should become undistinguishable from regular satellite galaxies on optical images.

## 2 Birth of Tidal Dwarf Galaxies: models, simulations

Observations give some clues on the formation mechanism of tidal dwarfs. In the young TDGs observed so far, the atomic hydrogen makes the bulk of their mass. Therefore gas should play a key role. On the theoretical side, several scenarios have been proposed, supported by various types of numerical simulations:

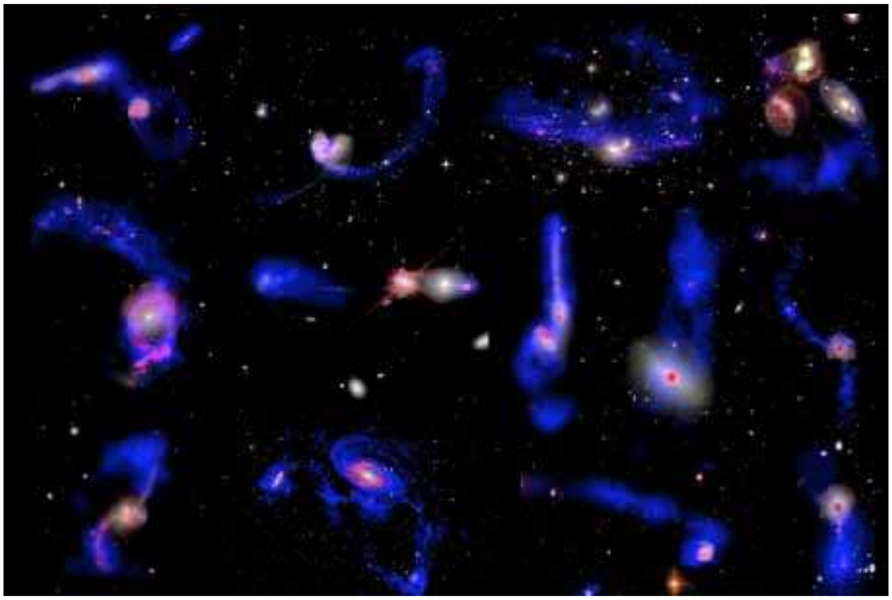

**Fig. 1** Sample of colliding systems exhibiting TDG candidates. The distribution of the gas is shown in blue and the star-forming regions in red.

• (1) *Local gravitational instabilities in the stellar component*. Simulations of mergers which only include the stellar component are apparently able to produce along tidal tails gravitational bound stellar objects, some reaching the mass of dwarf galaxies [1]. However it has been claimed that they might in fact be artifacts of the N-body simulations [30]
• (2) *Local gravitational instabilities in the gaseous component*. In simulations which include the gas component, real massive gas condensations may locally grow in the tails and form objects similar to TDGs [30]
• (3) *Ejection of Jeans-unstable gas clouds*. Due to the increased velocity dispersion induced by galaxy-galaxy interactions, the Jeans mass of the individual cloud complexes increases in the outer disks of the parent galaxies. They are then pulled out by tidal forces, become unstable and collapse when reaching large galacto-centric distances [11].
• (4) *A top–down kinematical scenario*. The *global* tidal field of galaxies with extended dark matter halos can efficiently carry away from their disk a large fraction of the gas, while maintaining its surface density to a high value [9]. In fact tidal forces contribute to stretch the gas only at low galacto-centric distances, i.e. at the base of the tail. As a result, gas accumulates near the tip of tidal tail, and then collapses and fragments, through a process apparently opposite to the bottom–up one favored with the Cold Dark Matter model for the building up of classical galaxies.
• (5) *The fully compressive mode of tidal forces*. At locations where tidal forces are compressive rather than destructive, star / cluster formation may be triggered and/or

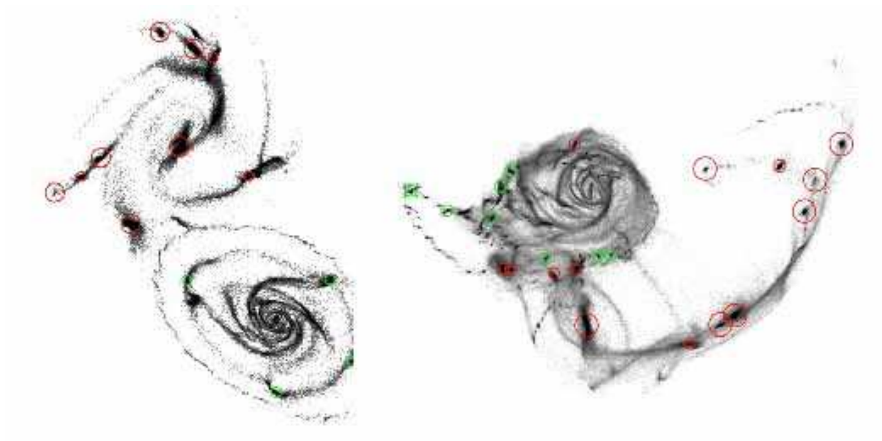

**Fig. 2** Formation of tidal dwarf galaxies in high resolution numerical simulation of a major merger [6]. Two snapshots are shown, resp. after the first encounter and the merger (Belles et al., in prep)

already formed stellar objects, such as TDGs, may be protected from disruption [24].
• (6) *Merger between Super-Star-Clusters*. SSCs with a range of masses may be formed in mergers. Some of them might merge to reach the mass of dwarf galaxies [12]. The TDGs born that way would then resemble the Ultra Compact Dwarf Galaxies (UCDs) identified in nearby groups and clusters of galaxies.

The variety of proposed scenarios tells how much having ad-hoc initial conditions and all necessary ingredients in the simulations is important: if the dark matter halo is truncated in the numerical simulations (to lower their computational cost), scenario (4) will not work; scenarios (2)-(5) require proper treatment of the gaseous component, including feedback. Scenario (6) needs high resolution, so as to resolve Super Star Clusters. Fig. 2 presents one of such simulations fulfilling most of these criteria. The numerical model used a total of 36 million particles, including 12 million "sticky" particles for the gas component, and minimal grid cell size of 32 pc [6]. The production of star clusters with masses down to $10^5$ $M_\odot$ was directly resolved in these simulations. The mass spectrum of objects produced during the merger seems to be bimodal. Two distinct families arise: (a) compact SSCs, with masses less than $10^8$ $M_\odot$ which seem pressure supported and may be the progenitors of globular clusters; (b) extended objects with masses above $10^8$ $M_\odot$ which are usually supported by rotation. The latter have the properties of observed Tidal Dwarf Galaxies. Thus TDGs are not simply the high mass end of SSCs, a conclusion that was also reached from the analysis of HST images [16]. Furthermore, analyzing snapshots of the simulation for a period of one Gyr, we found no evidence that the latter evolve into the former, via merging. The TDG progenitors are visible soon after the first encounter, in the outskirts of the colliding galaxies, at a time when the tidal tails have not yet completely unfolded. They quickly collect all their building material. After about

100 Myr, their mass is stabilized. Rotational support appears as well very early on. Only a few massive objects are formed later on within the tidal tails. Note however that star-formation and gas feedback are not properly handled with the sticky particles used in these simulations. Investigations may now be carried using fully hydrodynamical simulations [26].

## 3 Life of Tidal Dwarf Galaxies: dynamics

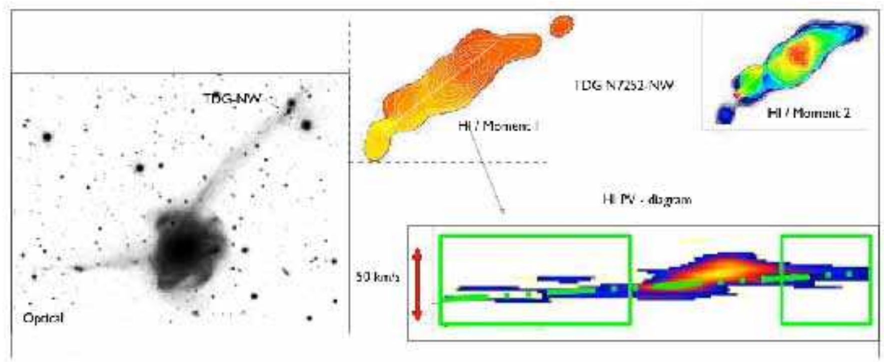


**Fig. 3** Prototypical merger NGC 7252. The moment maps of the HI towards the TDG candidate (top), as well as its position–velocity diagrams are consistent with rotation (Belles et al. in prep.)

Numerical models predict that TDGs, or at least the more massive of them, should be supported by rotation. Optical slit spectroscopy of numerous TDG candidates has been carried out [29, 18], showing strong velocity gradients, consistent with rotation, but also with artificial slit effects [28]. Integral field spectroscopy data [4], as well as high resolution HI and CO datacubes [15, 5] are available for several TDGs and confirm that TDGs rotate, though at velocities much lower than measured with slit spectroscopy. For the TDGs located in the collisional ring of NGC 5291, the data quality was sufficient to allow a determination of their total mass, and comparing it with the luminous mass (HI, $H_2$, stars), of their dark matter content. As predicted by numerical simulations and early estimates of the dynamical mass based on the millimeter CO line width [7], the inferred M/L is much lower than in regular, dark matter dominated dwarf galaxies. However an unanticipated mismatch by a factor of 2–3 between the dynamical and luminous mass has been noticed [5]. A similar discrepancy was found for the TDG candidate VCC 2062, in the Virgo cluster [10], and more recently in one of the TDGs hosted by the prototypical advanced merger NGC 7252. The results of this latter study are illustrated in Fig. 3.

Various hypotheses have been put forward to account for the missing mass in TDGs. Cosmological dark matter accreted from disrupted satellite galaxies [23] might be present in the disk of spirals and thus in TDGs. Theory of modified gravity, such as MOND, predicts rotation curves for TDGs similar to the observed ones [13, 20]. An alternative idea is that spirals disks contain dark baryons, for instance in the form of very cold molecular gas not accounted for by CO observations [22]. The presence of dark gas clouds in the Milky Way had been inferred using gamma rays [14]. In the far-infrared domain, Planck is also making a census of the molecular component not mapped by standard tracers. Whether it may explain entirely the missing mass observed in TDGs is still an open question.

## 4 Death of Tidal Dwarf Galaxies: life expectancy, census

If Tidal Dwarf Galaxies tell something about dark matter and thus about cosmology are they cosmological important objects? To answer this question, one should determine how many of them are produced per merger, and then how many manage to survive. Both simulations and observations may give clues on these issues.

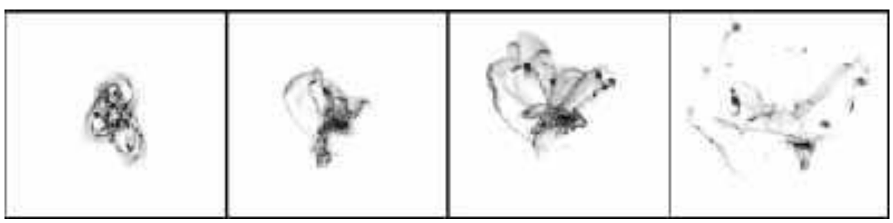

**Fig. 4** TDG formation at high redshift, probed by simulations of clumpy disk galaxies with a high gas fraction (Bournaud et al., 2010, submitted)

From the simple argument that, at high redshift, tidal collisions should have been numerous, some researchers reached the radical conclusion that most dwarfs in the Universe should have a tidal origin [21]. Since this is rather unlikely, the Cold Dark Matter paradigm, and the hierarchical mass assembly it implies have been questioned [17].

Analyzing a large set of numerical simulations, we concluded that the formation of TDGs was in fact not a very efficient process in galaxy collisions: specific conditions should be met, such as low impact velocities, up to 250 km $s^{-1}$, leading to mergers, prograde encounters, mass ratios up to 4:1– excluding minor mergers –, and above all initially extended gas in the parent galaxies [3]. Furthermore, only TDGs located near the tip of the tidal tails are able to survive more than 1 Gyr. The production rate is then about 1 TDG per *favorable* merger. Even if the merging rate increases with redshift, it would then be unlikely that TDGs contribute more than a few percent to the population of dwarf galaxies. However, the initial parameters of our simulations [3] are valid for nearby mergers. Simulations of mergers tuned for the distant Universe which in particular assume that the disk of the parent galaxies had a higher gas fraction (up to 50%) and was more turbulent, are presented in Fig. 4. They did not generate the very long tidal tails observed in nearby mergers. However a large number of clumps of matter, with typical masses of $10^8 - 10^9$ $M_\odot$, initially formed in the disks may be kicked out by the collision. Such objects, once independent, have all the properties expected for TDGs.

If such process is as efficient as these simulations show, the Local Universe should be full of such second generation, dark matter poor, dwarf galaxies. Is it really the case? The distribution of the Local Group dwarf spheroidals on specific planes/circles may suggest that they are old TDGs [19]. Given their location, even the Magellanic Clouds were speculated to have been synthesized in an old merger that built the present-day Andromeda galaxy [31]. However to validate such an hypothesis, one needs to check whether it is consistent with all the other properties expected for TDGs: lack of dark matter, specific star formation and chemical enrichment histories. And what is so far known about the properties of the neighbors of the Milky Way does not really support the tidal hypothesis.

Old TDGs remain to be found, first looking at environments where they are expected to have formed efficiently, i.e. where major mergers have likely occurred. If Early-type galaxies result from major mergers, some of their satellites might be of tidal origin. Fig. 5 presents deep optical images of a nearby elliptical galaxy that revealed the presence of three gas–rich TDG candidates, which have likely formed 2-3 Gyr ago.

Such systematic census of old TDGs, coupled with new numerical simulations of mergers, with a proper treatment of the gas and star-formation, should be pursued to determine the real numerical importance of tidal dwarfs.

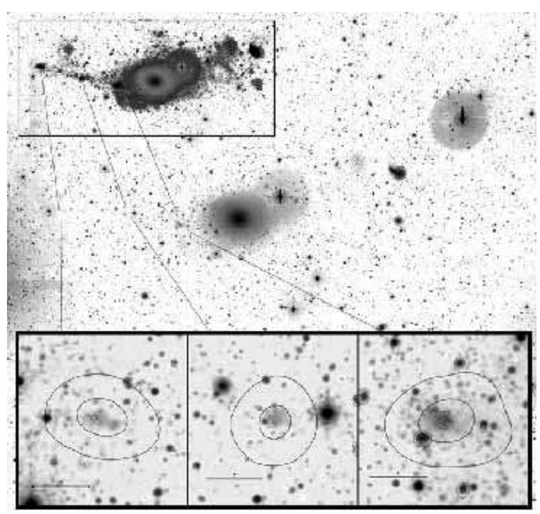

**Fig. 5** Discovery of old TDGs around an elliptical galaxy with the CFHT MegaCam camera. The image was obtained as part of the ATLAS$^{3D}$ survey (Cappellari et al., 2011). The three candidates which have morphologies of dEs but are gas–rich – see the bottom g–band images with contours of the HI emission from the WSRT (Serra et al., in prep.) superimposed – lie along a 160 kpc long tidal tail, visible on the top image, where low surface brightness features have been enhanced. The merger has an estimated age of 2-5 Gyr (Duc et al., 2011, submitted)

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