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# Identifying old Tidal Dwarf Galaxies in Simulations and in the Nearby Universe

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**Abstract.** Most Tidal Dwarf Galaxies (TDGs) so-far discussed in the literature may be considered as young ones or even newborns, as they are still physically linked to their parent galaxies by an umbilical cord: the tidal tail at the tip of which they are usually observed. Old Tidal Dwarf Galaxies, completely detached from their progenitors, are still to be found. Using N–body numerical simulations, we have shown that tidal objects as massive as $10^9$ solar masses may be formed in interacting systems and survive for more than one Gyr. Old TDGs should hence exist in the Universe. They may be identified looking at a peculiarity of their "genetic identity card": a relatively high abundance in heavy elements, inherited from their parent galaxies. Finally, using this technique, we revisit the dwarf galaxies in the local Universe trying to find arguments pro and con a tidal origin.

## 1. Introduction

The presence of compact star-forming regions in the tidal tails of colliding galaxies is commonly observed. The formation, in that environment, of super-star clusters with masses up to those of globular clusters has also often been reported (e.g., Knierman et al., 2003). The existence of even more massive tidal objects, with global properties characteristics of dwarf galaxies, has been claimed for more than a decade (see the review by Duc & Mirabel, 1999). But whether such "Tidal Dwarf Galaxies" are genuine galaxies – i.e. they are gravitationally bound entities – is still strongly debated (see in this volume the contribution by Hibbard & Barnes and that of Amram et al. and Braine et al. for an alternative view). But perhaps the more important issue of whether TDGs survive, escape from their parent galaxies, and significantly contribute to the overall population of dwarf galaxies, is a matter of speculation. Indeed, a more plausible fate is their tidal destruction or their falling back onto their progenitors. There are two ways to tackle the problem: using numerical simulations of interacting galaxies and following in them the buildup and evolution of tidal objects, or trying to identify in catalogs of dwarf galaxies those which might have a tidal origin. We have explored both approaches.

## 2. Old Tidal Dwarf Galaxies in numerical simulations

Since the seminal work by Toomre & Toomre (1972), numerous numerical simulations have been made to study the evolution of colliding galaxies. If the reliability of the computer calculations has often been checked from their ability to produce realistic tidal tails, most of these efforts were focussed in understanding what happens in the most central regions. The simulations by Barnes & Hernquist (1992) were the first ones to show the formation, out of tidal material, of bound clumps with masses of up to $10^8 M_\odot$, distributed all along the tails. As stressed later on, among others by Hibbard & Mihos (1995), the tidal material will quickly fall back unless it was originally sent to large distances where it may survive for more than a Hubble time. In real interacting systems, however, this is precisely where the most massive TDG candidates, with apparent masses of a few $10^9 M_\odot$, are found (unless these are just the result of projection effects; see arguments against that idea in the contribution by Amram et al. in this volume). Very recently, we were able to reproduce for the first time in N-body simulations the formation of such massive objects near the tip of long tidal tails (Bournaud, Duc & Masset, 2003). This could be achieved when we adopted very extended dark matter halos for both parent galaxies. Such large halos are actually consistent with theoretical cosmological models; they are however usually disregarded and truncated in numerical simulations because they consume a large number of particles (and CPU time) but have only a minor impact on the merger remnant where most of the attention is. Figure 1 presents our simulations; it shows how the gas of one galaxy with an extended dark matter halo reacts to the perturbation of another one of the same mass. Note in particular how the gas piles up at the tip of one of the tidal tails. Self-gravity makes it become a compact object with a mass of $10^9 M_\odot$. Two Gyr after the first encounter and the dissolution of the tails, it is still visible on a quasi-circular orbit at large radii and appears as a classical companion galaxy. In simulations where long tidal tails are able to form (and hence for which the colliding galaxies have the adequate orbital parameters and relative velocities), the production of massive, long-lived, tidal objects is not exceptional. However, we still need to explore more systematically the parameter space to obtain quantitative predictions on the production rate of TDGs. In any case, our preliminary study indicates that massive tidal objects may be created during tidal collisions, and have a life time long enough to become old Tidal Dwarf Galaxies, as previously defined. Therefore searching for such objects in the real Universe makes sense.

## 3. Identifying old Tidal Dwarf Galaxies

How to identify old TDGs when they have no obvious connection – an optical stellar bridge or an HI gaseous bridge – to any nearby merging galaxy ? Hunter et al. (2000) proposed to look at their dark-matter content, expected to be small if TDGs are made of disk material and if most of the dark matter is distributed in a halo. Such objects should also have a special location on the Tully-Fisher diagram. However, by far the easiest way is an unusually high metallicity. Standard isolated galaxies follow a fair correlation between their luminosity (mass) and their metallicity. The less massive ones tend to be less

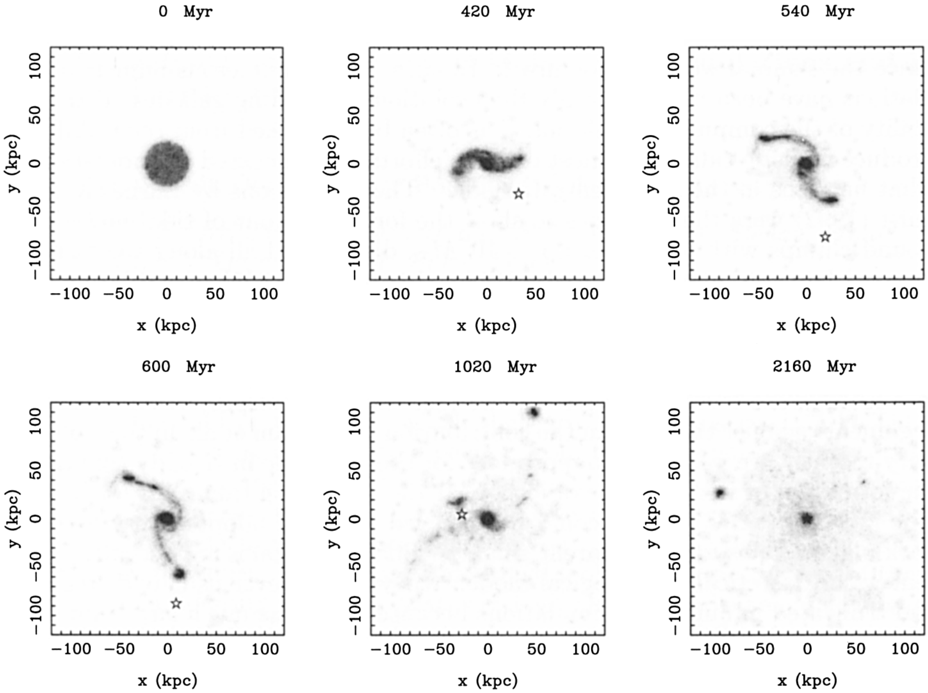

Figure 1. Response of the gaseous disk of a galaxy to a tidal interaction. The gas column-density is plotted in grayscale. The center of the second galaxy is represented by the star symbol. The truncation radius of the dark haloes is extended up to 10 times the radius of the stellar disks (see details in Bournaud, Duc & Masset, 2003)

metal-rich because they are less able to retain their heavy elements that the most massive ones. This correlation is shown in Figure 2. Galaxies departing form that relation and having an oxygen abundance which is too high for their luminosity can be considered as TDG candidates. Indeed tidal dwarfs are made of recycled, pre-enriched, material. In fact, the oxygen abundances of young tidal objects (observed near confirmed mergers, and shown in Fig. 2) have an oxygen abundance of about 1/2 - 1/4 solar, which is independent of their luminosity, and typical of that of the external regions of spiral disks from where their building material originally comes.

One should note that other phenomena can account for a high metallicity in a dwarf galaxy . An external confinement effect by a dense intergalactic medium may prevent it from expelling its heavy elements. Some dwarfs could also be the remnants of more massive and metal–rich galaxies that have been disrupted by collisions (see the contribution of K. Bekki in this volume). Those effects should principally apply in dense environments such as in clusters of galaxies.

As a side effect, molecular gas as traced by the CO emission should be more easily detectable in pre-enriched dwarfs whereas it is not observed in the metal

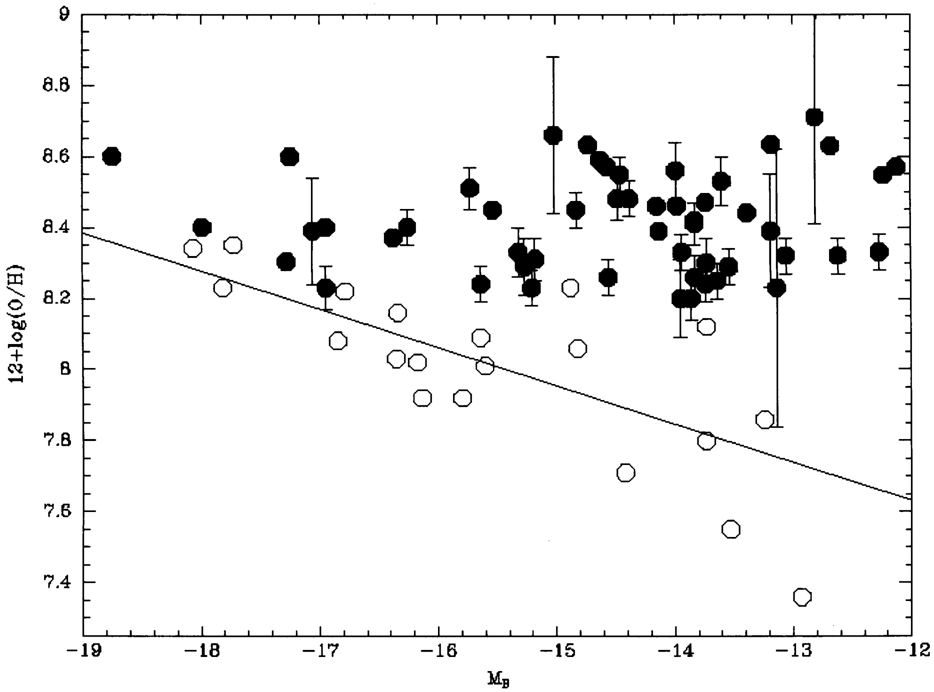

Figure 2. Luminosity-metallicity relation for a sample of isolated nearby dwarf galaxies (open circles; Richer & McCall, 1995) and in the HII regions of a sample of young tidal objects (black circles; Weilbacher et al, 2002). The oxygen abundances versus absolute blue magnitudes are plotted.

poor classical dwarfs. Strong CO emission has been detected in most massive TDGs (Braine et al. 2001, and his contribution in this volume).

## 4. Old Tidal Dwarf Galaxies in the nearby Universe

Is there any observational evidence that TDGs may survive for at least 500 Myr and may hence already be considered as old ? First of all, a few confirmed TDGs are observed in the vicinity of advanced mergers. In these systems, the nuclei of the colliding galaxies have already merged. The associated time scale given by numerical simulations is typically 0.5-1 Gyr. Examples of such objects are shown in Figure 3. In those, the tidal tails are already quite faint whereas the most massive and distant condensations are still clearly visible. Optical spectroscopy indicates that all of them have oxygen abundances consistent with those expected for a tidal origin.

We explore in the following whether even older, completely detached, TDGs are present in catalogs of classical dwarf galaxies, starting with the Local Group. Our closest companion, the Sagittarius dwarf galaxy, is currently being eaten by

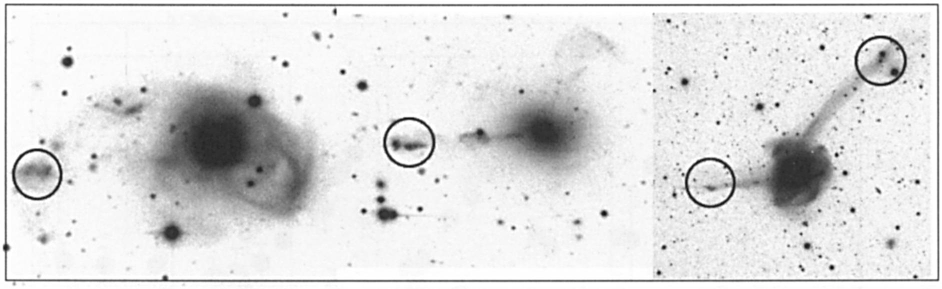

Figure 3. Tidal Dwarf Galaxies (encircled) in the vicinity of three advanced mergers. The dynamical age of these systems are at least 500 Myr.

the Milky Way. Measuring with high-resolution UVES spectra element abundances of a sample of individual stars, Bonifacio et al (2004) estimate that a substantial metal rich ( [Fe/H]=-0.25 ) population exists in Sgr. Such a high degree of chemical enrichment either suggests that Sgr was a much larger galaxy in the past, or that it was detached from the LMC or the MW during their interaction. The distribution of the other dwarf spheroidals in the Local Group along a great circle suggests that they also may have been involved in this collision (Lynden-Bell, 1982). However, their metallicities, usually considered to be low and their high dark matter content (although challenged by Kroupa, 1997) make them unlikely TDG candidates.

One of the closest groups of galaxies, the M81 group, is well known for the spectacular tidal interaction in which three of its members are involved: M81, M82 and NGC 3077. Numerous TDG candidates or intergalactic HII regions were identified in that environment (Makarova et al., 2002; Durrell et al. in this volume); among them The Garland object (Walter et al., in this volume), and the protogalactic molecular cloud near Holm IX are best studied. Whereas, on optical images, the latter intergalactic objects appear "detached" , HI maps show that they actually lie towards the prominent gaseous tidal tail linking the three main galaxies and in which they were probably born. They cannot hence be considered as old TDGs.

The closest cluster of galaxies, Virgo, has its own TDG candidate: a HI, CO and Oxygen rich low-surface brightness galaxy, not too far from the lenticular NGC 4694 (Braine et al., in this volume). Studying the early-type dwarf galaxies in the nearby clusters of Coma and Fornax, resp. Rakos et al. (2000) and Poggianti et al. (2001; see also her contribution in this volume), found that a significant fraction of them deviate from the metallicity-luminosity relation; the youngest ones being the more metal-rich ones. We reached the same conclusion in our own complete survey of HI-rich, star–forming dwarf galaxies in the Hydra (Duc et al., 2001) and Hercules (Iglesias-Paramo et al., 2003) clusters: about 30% of them have unusually high oxygen abundances in their HII regions.

It is still premature to conclude from these surveys whether old TDGs contribute significantly to the population of dwarf galaxies. As already mentioned, other phenomena may account for the deviating metallicities. On the other hand, selection criteria only based on metallicities disregard TDGs that would have formed out of the most external and metal–poor disk material, or those formed in the early Universe when collisions were more frequent and galaxies less metal–rich. Likely the frequency of TDGs will depend on the environment. Compact groups may be a particularly favorable one (Hunsberger et al., 1996). Our numerical simulations indicate that long-lived (i.e., formed at least 1-2 Gyr ago) TDGs should exist. Whether they will survive for a Hubble time is still unknown. One may however note that the falling back onto a giant galaxy is also the fate of numerous classical dwarfs.

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