

TIDAL DWARF GALAXIES

P.-A. DUC

*ESO, Karl-Schwarzschild Strasse 2
D-85748 Garching bei München, Germany
<pduc@eso.org>*

AND

I.F. MIRABEL

*CEA, SAp, C.E. Saclay
91191 Gif/Yvette Cedex, France, & Instituto de Astronomía y
Física del Espacio, Argentina
<mirabel@discovery.saclay.cea.fr>*

Abstract. We review the observational evidences for tidal dwarf galaxies, a class of small galaxies formed out of the tidal debris of collisions between massive galaxies. Tidal dwarfs are found far from the interacting parent galaxies, associated with massive clouds of atomic hydrogen located at the tip of long tidal tails. These newly formed galaxies are among the best cases for the study of galaxy formation in the nearby Universe.

1. Introduction

Most studies of interacting/merging systems focus on their central regions, which are dramatically affected by the collision. In particular the gas often loses angular momentum and sinks into the galactic cores, triggering nuclear starbursts and the formation of young star clusters. On the other hand tidal forces may pull out from the outer regions into intergalactic space stars and interstellar gas shaping rings, bridges, plumes and tails. The amount of matter lost during that outflow can be as large as one third of the mass in the pre-encounter disks. In interacting systems the bulk of the atomic hydrogen is in fact located outside the galaxy bodies (see review by F. Combes in this volume and examples below).

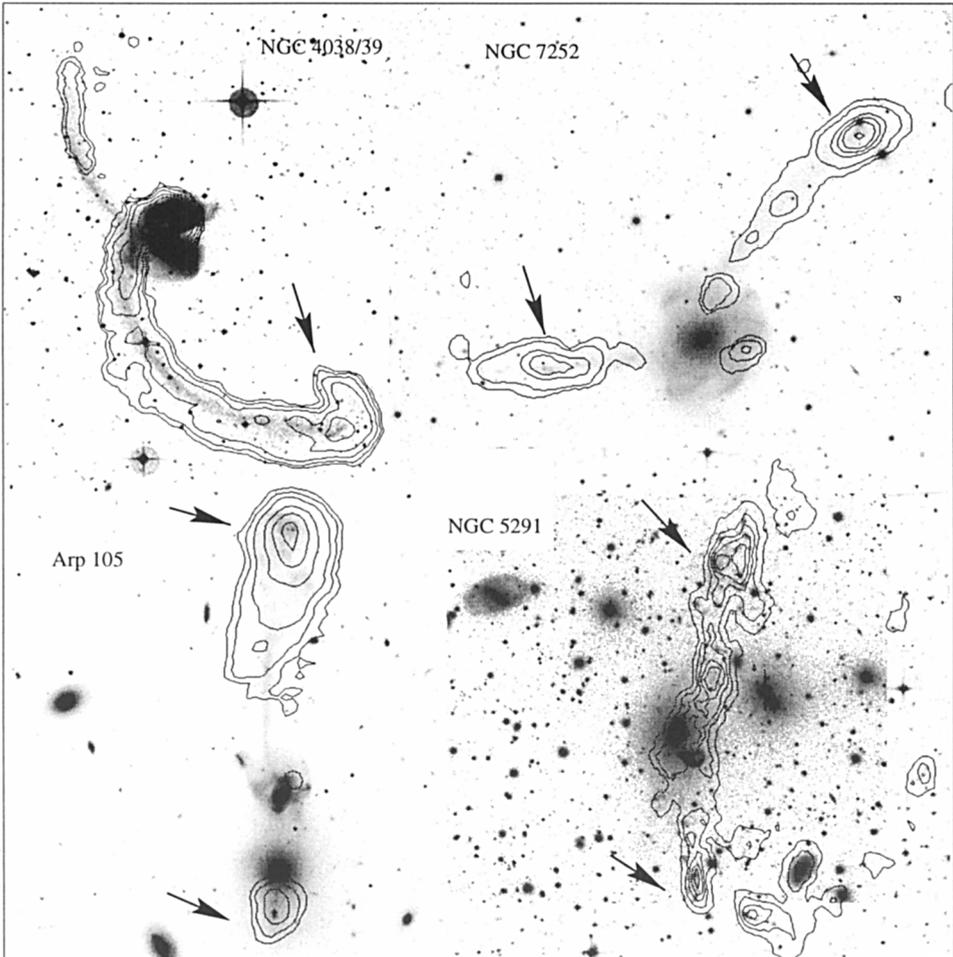


Figure 1. Tidal dwarf galaxies in four interacting systems. They are seen at the end of optical tidal tails or HI plumes (black contours) and indicated by arrows. The optical images are clock-wise from the Digital Sky Survey, Duc (1995), Duc & Mirabel (1997) and Duc & Mirabel (1994). The HI maps are from Hibbard et al. (1997), Hibbard et al. (1994), Malphrus et al. (1997) and Duc et al. (1997)

Nevertheless until recently only few studies have been devoted to the properties of tidal features (e.g. Wallin 1990; Schombert et al. 1990). Tails are basically used as tracers of past minor/major mergers. Their shapes are useful to constrain the parameters in numerical models of the collision, including the mass of dark matter in the parent galaxies (Dubinski et al. 1996). The interest in these collisional debris was revived when it was discovered that they host active star forming regions (Schweizer 1978; Mirabel et al. 1992) and are actually a nursery of small galaxies, the so-called “tidal

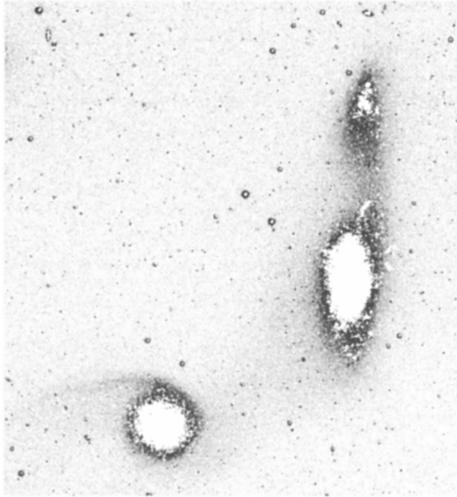


Figure 2. Optical image of the disk-disk system NGC 2992/93 with the H α emission superimposed in white. Note how star formation as traced by the ionized gas is enhanced simultaneously in the galaxy body and at the tip of the tidal tail.

dwarf galaxies” (hereafter TDGs). New optical and HI observations have shown that TDGs actually form a class of “recycled” objects with some characteristics similar to the more classical dwarf irregulars (dIrrs) and blue compact dwarf galaxies (BCDGs). Here we review prototype interacting systems that exhibit the formation of tidal dwarfs, detail the general properties of TDGs and give some hints for their origin and future evolution.

2. Case studies

We have carried out multi-wavelength observations of several interacting systems in the nearby Universe. Optical imaging and spectroscopy were obtained with the CFHT at Mauna Kea and the ESO/NTT at la Silla Observatory; near-infrared imaging at the ESO/MPI 2.2m, and HI at the VLA. HI data come either from our own observations, or were kindly provided to us by other groups.

Fig. 1 and Fig. 2 present different examples of interactions: spiral-spiral collisions (NGC 4038/39, “The Antennae”; NGC 2992/93), complete merger between spirals (NGC 7252) and encounters involving early-type galaxies (Arp 105, “The Guitar galaxy”; NGC 5291). Long tidal tails are clearly seen emanating from the parent galaxies. At their tip, at distances up to 100 kpc from the nuclei, small irregular objects are found with absolute magnitudes typical of dwarf galaxies. They host blue compact clumps

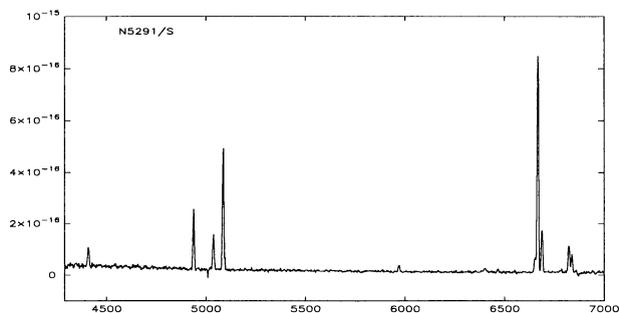


Figure 3. Optical spectrum of one of the tidal dwarfs near NGC 5291 showing emission lines typical of HII regions. From Duc & Mirabel (1997).

that also show up in maps of the ionized gas (see Fig. 2).

The spectra of the optical condensations exhibit emission lines, typical of HII regions ionized by massive OB stars younger than 10 Myrs (e.g. Fig. 3). Given the time scale for the formation of clumps in tails – typically 1 Gyr –, the stars at the tip of the antennae must have been born in situ. Therefore interactions not only trigger star formation in the main body of the parent galaxies but also far from the nuclei in the remote tidal features.

The contours of the HI column density are superimposed on the optical images in Fig. 1. It is clear that the central regions of the parent galaxies contain little atomic gas, whereas the optical tails, and especially the tidal dwarfs at their tip, are associated with HI clouds as massive as $6 \times 10^9 M_{\odot}$. Similar HI distributions were observed by Hibbard & van Gorkom (1996) in several other interacting systems. On the other hand the molecular gas tends to concentrate in the central regions fueling the nuclear starburst of interacting galaxies (e.g. Young & Scoville 1991). Such a spatial segregation of the different gas components is clearly seen in Arp 105 (Duc et al. 1997; Fig. 1).

3. Properties of tidal dwarf galaxies

Table 1 summarizes the statistics for the main properties of the 20 TDGs sofar studied.

3.1. STELLAR POPULATIONS AND GAS CONTENT

Tidal dwarf galaxies may be made of two stellar components: young stars, formed from the recent collapse of expelled HI clouds, and possibly an older star population coming from the disk of their parent galaxies. Using our aperture photometry and spectroscopic data, we could estimate the relative proportion of both populations and conclude that TDGs actually

TABLE 1. Integrated properties of tidal dwarf galaxies

Properties	Units	Mean	Min	Max
Absolute Blue Magnitude	mag	-14.8	-12.1	-18.8
$B - V$ color index	mag	0.3	0.0	0.7
Star Formation Rate	$\log(M_{\odot}/\text{year})$	-1.1	-3.6	0.3
HI Mass	$10^9 M_{\odot}$	1.6	0.2	6.0
O Abundance	$12 + \log(\text{O}/\text{H})$	8.5	8.3	8.6

split into two categories 1) extremely young objects, most probably forming their first generation of stars (e.g.: the dwarfs around NGC 5291, Duc & Mirabel 1997), with high star formation rates equivalent to those observed in blue compact dwarf galaxies, and 2) galaxies dominated by an old stellar population originally from the disk of their progenitors, and that look like dwarf irregulars (e.g. the galaxy North of NGC 2992, Fig. 2). Both type of galaxies separate on an optical/near infrared color-color diagram, as shown in Fig. 4. The optical $B - V$ colors of the “young” TDGs and BCDGs are similar. The near-infrared $V - K$ color index of TDGs appears though to be redder on average, which could be due to a difference in metallicity between both classes of objects. The colors of the “old” TDGs are similar to these of the outer parts of their parent galaxies.

In all these objects, the equivalent width of the optical Balmer lines indicates that the current star-forming episode is younger than 10 Myrs. Important HI reservoirs – between $5 \times 10^8 M_{\odot}$ and $5 \times 10^9 M_{\odot}$ – can sustain the star formation for several Gyrs.

The molecular gas content of tidal dwarfs is still largely unknown. Smith & Higdon (1994) failed to detect any CO emission in the tails of a few interacting systems. CO was also reported to be very weak in blue compact dwarf galaxies despite their high star formation rate. This was interpreted as a metallicity effect. However TDGs seem to be quite metal rich systems in which CO should be easier to detect.

3.2. METALLICITY

Fig. 5 shows the oxygen abundance vs. absolute magnitude of a sample of TDGs and nearby dIrrs. The abundances have been estimated in the ionized gas from the $[\text{OIII}]/\text{H}\beta$ line ratio. Their uncertainties are discussed in Duc & Mirabel (1997). Clearly TDGs are more metal rich than classical dwarfs of the same luminosity. They have metallicities $Z_{\odot}/3$ on average, a value that is typical of the outer regions of spirals. They do not follow the correlation found for field dwarf and giant galaxies between luminosity

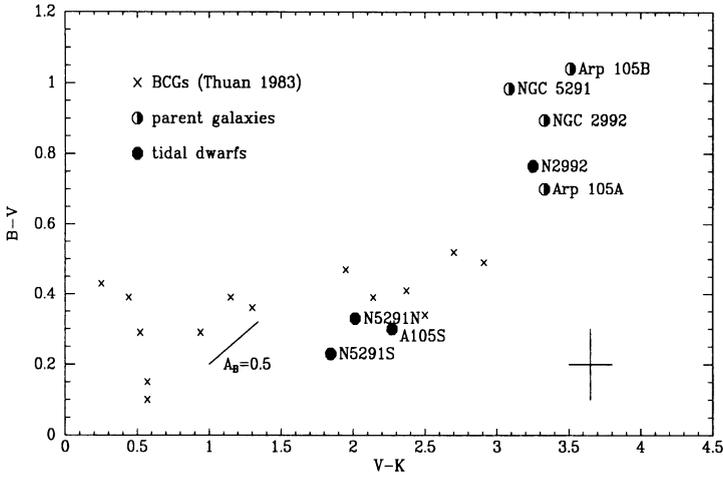


Figure 4. Color-color diagram of tidal dwarfs. For reference, the colors of the outer regions of the parent galaxies are also indicated and a sample of blue compact dwarfs has been added. The cross at the lower right corner indicates typical error bars.

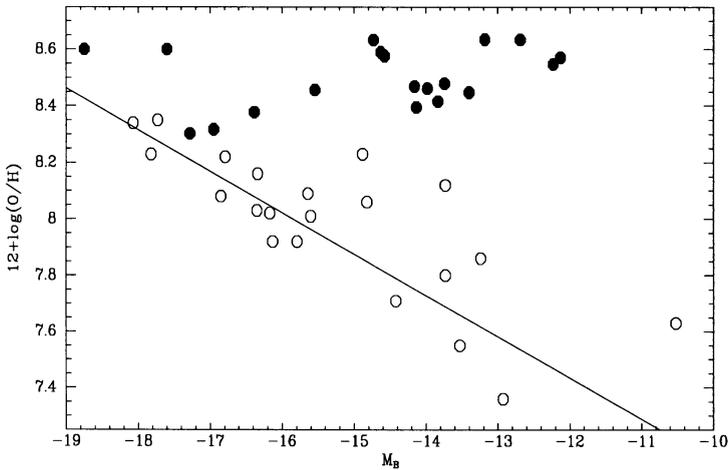


Figure 5. Oxygen abundance vs absolute blue magnitude for our sample of tidal dwarfs (black points) and a sample of isolated dwarf galaxies (open points; from Richer & McCall 1995).

(hence mass) and metallicity. Being “recycled” objects, formed from pre-enriched material, tidal dwarfs got as an heritage from their parents this relative high metal content.

3.3. DYNAMICS

Little is still known about the internal dynamics of tidal dwarfs. First indications are that the most massive TDGs may be gravitationally bound (Hibbard et al. 1997; Malphrus et al. 1997). Hints for rotation were found in the HI cloud associated with a TDG in Arp 105 (see Fig. 6). Furthermore, strong velocity gradients of the ionized gas have been found in several objects, which suggests rotation too (Fig. 7). Therefore, some objects in tidal tails may already be dynamically independent. Further 3D kinematical studies would be necessary to verify this assertion and estimate their dark matter content, predicted to be low in numerical simulations (Barnes & Hernquist 1992).

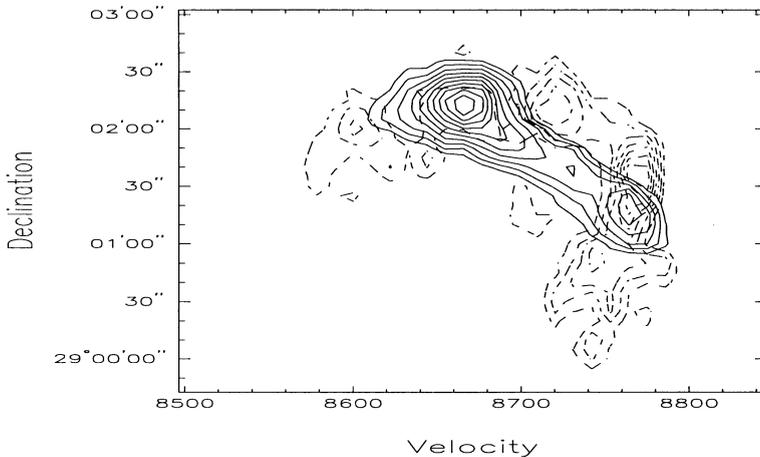


Figure 6. Position-Velocity diagram of the HI northern tidal tail in Arp 105. Two components were identified: the expanding HI tidal tail (dashed contours) and a kinematically decoupled, possibly rotating, component (continuous contours) associated with the formation of a tidal dwarf at the tip of the tail; adapted from Duc et al. (1997).

4. Origin and evolution of tidal dwarf galaxies

4.1. INGREDIENTS FOR THE FORMATION OF TDGS

Obviously star-forming tidal dwarf galaxies only form after an encounter between gas-rich galaxies. The nature of the collision is a priori also important. One should differentiate disk-disk collisions from collisions involving early type galaxies. In the first case, tidal features are made out of expelled gas and stars. In the second case, stellar tails are difficult to form because of the pressure-supported nature of the stellar dynamics of ellipticals, whereas the HI component, mostly of external origin and often supported by rotation, is easier to disrupt. Pure HI tails will then be formed. Finally there are

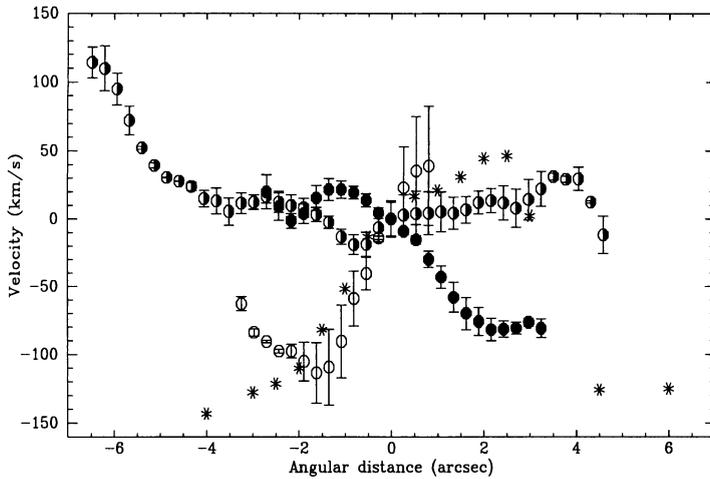


Figure 7. Velocity profiles of the ionized gas for several tidal dwarfs; adapted from Duc & Mirabel (1997).

instances where HI and stellar tails have different positions and extensions. The initial properties of the resulting TDGs will depend on their location. This explains why two categories of TDGs have been identified.

4.2. MODELS FOR THE FORMATION OF TDGS

Models for the formation of TDGs put forward two mechanisms: a local dynamical instability in the old stellar populations of tidal tails, followed by accretion of gas (Barnes & Hernquist 1992) or the collapse of a supermassive cloud triggering precipitous star formation activity (Elmegreen et al. 1993). Because of the variety of the stellar and gas content of TDGs one could argue that both mechanisms play a role: the stellar scenario would apply for TDGs born in HI+stellar tails; the gas scenario for TDGs born in pure HI tails. However it seems that even for TDGs belonging to the first category, the HI masses and resulting potential well are large enough to trap the old tidal star population. As a consequence, despite the diversity of initial environments, all TDGs may have been formed by the same mechanism.

What causes the collapse of tidally expelled gas clouds is still unclear. Other environmental effects such as ram pressure by the intergalactic medium may play a role. Strong asymmetries of the HI distribution in some interacting systems suggest some kind of compression at the interface with the IGM. Hawarden & Chaytor (1996) find in NGC 5291 a possible expansion of the x-ray emission along the HI tail and its associated HII regions. This hypothesis should be further investigated and modeled. In x-ray clus-

ters, besides tidal forces, ram pressure could even have taken part in the pulling out of the HI clouds from spirals known to be HI deficient. Instances of enhanced star formation in stripped clouds have been presented by J. Kenney (this volume).

4.3. SURVIVAL OF TDGS

Do tidal dwarf galaxies contribute significantly to the overall population of dwarf galaxies? The answer to this fundamental question relies on the knowledge of the frequency of tidal interactions between galaxies, which is still controversial, and on the life-time of TDGs. The latter is limited by the hostile environment for TDGs located in the vicinity of giant parent galaxies. They may fall back on their progenitors in time scales of 1 Gyr, as put forward by Hibbard & Mihos (1995), or be tidally disrupted. It is therefore expected that only the most massive TDGs that are far away from their progenitors will survive in timescale of Gyrs. This limits the number of galaxies produced to one or two per colliding system. In this context, it is not surprising that no luminous star-forming TDGs are found at the base of the tidal tails too close from the parent galaxies.

From an observational point of view, the census of TDGs is not an easy task. TDGs should obviously be searched in the environment of interacting galaxies and a priori in high density regions such as groups and clusters. Instances of small star-forming entities were discovered in the arms of the Stephan's Quintet by Ohyama et al. (1997). Hunsberger et al. (1996) claim from the analysis of photometric data that half of the dwarf galaxies in Hickson compact groups could be of tidal origin. However, one should note that once the stellar/gaseous "bridge" between the parent and child galaxies has dissipated, it is difficult to re-establish a link between the two. Our study has shown that a good genetic fingerprint of TDGs is their high metallicity. In this respect, several studies have put forward trends for dwarf galaxies in clusters to be more metallic than field dwarfs (Bothun et al. 1985; Vilchez 1995). Since the collision rate is enhanced in denser environments, it is tempting to argue that a significant fraction of dwarfs in clusters could be recycled objects. A bimodal star formation history is also a strong signature for tidal dwarfs. Evolutionary Synthesis Models simulating a burst of star formation on top of the underlying component of old galaxies reproduce well the TDG star formation history and will give constraints for their future evolution (Fritze - v. Alvensleben & Duc 1997).

4.4. TDGS AS LABORATORIES

Tidal dwarf galaxies are of particular interest to studies of galaxy formation in the nearby Universe. They are recently formed galaxies from the collapse

of massive gas clouds. Contrary to BCDGs, TDGs born in pure HI tails are not contaminated by old stellar populations, allowing a better study of the parameters that rule star formation in galaxies.

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