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H I Recycling: Formation of Tidal Dwarf Galaxies

P.-A. Duc

CNRS and CEA-Saclay, Service d'astrophysique, Orme des Merisiers, 91191 Gif sur Yvette cedex, France

E. Brinks

Departamento de Astronomía, Apdo. Postal 144, Guanajuato, Gto. 36000, Mexico

Abstract. Galactic collisions trigger a number of phenomena, such as transportation inward of gas from distances of up to kiloparsecs from the center of a galaxy to the nuclear region, fueling a central starburst or nuclear activity. The inverse process, the ejection of material into the intergalactic medium by tidal forces, is another important aspect and can be studied especially well through detailed H I observations of interacting systems. These studies have shown that a large fraction of the gaseous component of colliding galaxies can be expelled. Part of this tidal debris might fall back, be dispersed throughout the intergalactic medium or recondense to form a new generation of galaxies: the so-called tidal dwarf galaxies. The latter are nearby examples of galaxies in formation. The properties of these recycled objects, and different ways to identify them, are reviewed here.

1. Recycling the H I gas

The VLA and other synthesis arrays have, for twenty years and more, revealed the spectacular distribution of the atomic hydrogen (H I) in interacting systems. Long tidal tails that are even more prominent than their optical counterparts, bridges, and ring-like structures are among the many weird and wonderful features which show up in high resolution maps (see Schiminovich et al., this volume). Because in general the H I in disk galaxies extends well beyond the optical R_{25} radius, this atomic hydrogen reacts very efficiently to any external perturbation as evidenced by the fact that most of the neutral gas is found outside the colliding disks. In systems like Arp 105 and NGC 7252 (see Fig. 1), up to 90% of the gas visible at 21 cm is situated in the intergalactic medium (IGM) and little, if any gas remains within the parent spirals. In addition to gas being actively removed, a large part of the original H I has likely been funneled inward where it was transformed into another phase (see review by Struck 1999).

The fate of the tidally expelled gas will largely depend on its density and location with respect to the interacting galaxies. Whereas the clouds closest to the interacting (or merging) pair will fall back at timescales of a few Myr (Hibbard & Mihos 1995), the most distant ones will become gravitationally un-

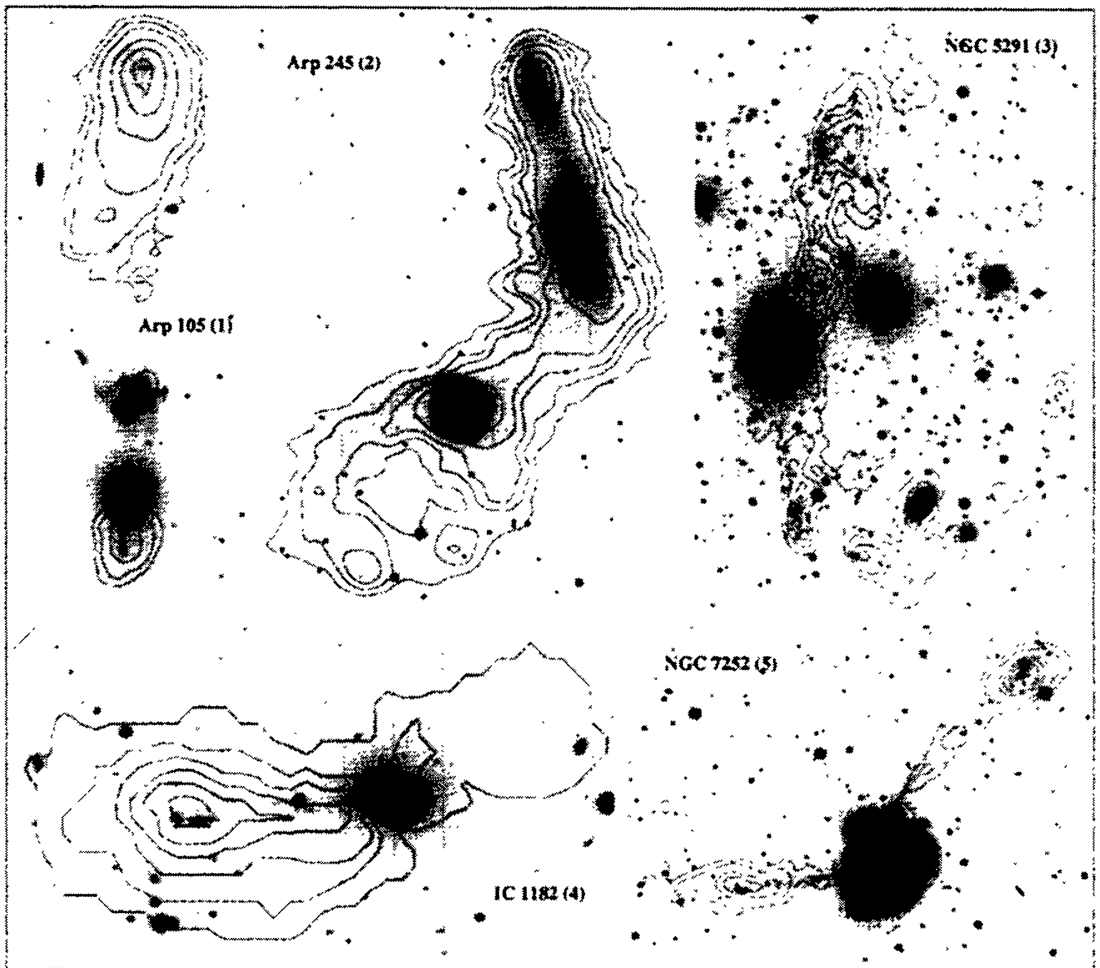

Figure 1. H I distributions for a sample of interacting systems which have formed some tidal dwarf galaxies. The H I contours are superimposed on optical V–band images; references for the H I VLA data: 1) Duc et al. (1997); 2) Duc et al. (2000); 3) Malphrus et al. (1997), and Duc & Mirabel (1998); 4) Dickey (1997); 5) Hibbard et al. (1994).

bound. They might slowly diffuse and enrich the IGM with heavy elements or the stars might even form the basis of the faint background light in the intracluster medium (ICM) if the interacting system belongs to a cluster. Under certain conditions, however, tidal debris may be recycled. If self-gravity is sufficiently large, expelled clouds will condense and collapse again to build new star-forming objects. Offspring as massive as Magellanic dwarf irregular galaxies has been observed around several interacting systems (see for example Fig. 1). Generally situated at the tip of 50–100 kpc long tidal tails, they are referred to as Tidal Dwarf Galaxies (TDGs). The total gas fraction that could end up in a TDG is as yet largely unknown and it is hoped that numerical simulations might one day get a handle on this. Observationally, H I clouds towards TDGs as massive as 5 10^9 $M_\odot$ have been measured.

2. Forming tidal dwarf galaxies

Not only H I clouds are expelled during tidal interactions, but any material that was originally (rotating) in a disk, in particular the stars. Therefore TDGs are mixed bags, composed of young stars formed *in situ* from collapsing gas clouds and an older population pulled out from their parent galaxies. The latter component may be unimportant in systems involving gas-rich early type galaxies (i.e. NGC 5291, Duc & Mirabel 1998; see also Fig. 1). Instabilities in the gaseous — H I — component seem to be the driving factor in the formation of TDGs. Star formation occurs at rates which might reach $0.1\,M_\odot\,yr^{-1}$. Given that TDGs contain huge H I reservoirs, typically $10^9\,M_\odot$, it is to be expected that the relative importance of an older stellar population will decrease with time as star formation proceeds. Appreciable quantities of molecular gas have also recently been detected in TDGs by Braine et al. (2000). They suggest that this gas has been formed *in situ* out of the collapsed H I.

3. Identifying tidal dwarf galaxies

Tidal objects will survive provided that they have a potential well that is deep enough to sustain themselves against internal or external disruption. When identifying TDGs, it is therefore important to check that they are not simply the agglomerated debris of a collision but are self-gravitating entities (Duc et al. 2000). One should hence try to distinguish those tidal features that are kinematically decoupled from their host tails, the kinematics of which is governed by streaming motions. Because of the difficulty of obtaining high-sensitivity, high-resolution H I data, and problems related to projection effects along the line of sight, this is a difficult task that requires a careful examination of the available datacubes, such as those provided by synthesis radio observations (for the neutral gas component), and Fabry-Perot or any integral field instrument (for the ionised component). Addressing the stellar kinematics would be even more challenging. So far, evidence for such self-gravitating clouds have been found in the interacting systems Arp 105 (Duc et al. 1997; see Fig. 2), NGC 5291 (Duc & Mirabel 1998), and perhaps Arp 245 (Duc et al. 2000).

It is one thing to pick out TDGs which are still linked to the tidal tails out of which they formed. But how can one recognise old tidal dwarf galaxies that would have lost their physical connection with their parent galaxies as the tidal tail linking it vanishes with time? One might make use of three special properties of TDGs. First of all, their metallicity: due to the fact that they are recycled material, it is much higher than that of classical dwarf galaxies of the same luminosity (Duc et al. 2000). The oxygen abundance of recently formed TDGs averages out at one third of solar, i.e., the abundance of spirals at or slightly beyond the optical R_{25} radius. Secondly, it is expected that TDGs contain little if any dark matter (DM) *if* DM in their progenitors was distributed in a large halo, as is traditionally assumed (Barnes & Hernquist 1992). If, however, DM is present in disks, for instance in the form of cold molecular gas (Pfenniger et al., this volume), DM-dominated tidal tails should form and TDGs would have a substantial DM content. Finally, the stellar population of TDGs should at least be bimodal: a fraction of their stars has originally come from the parent

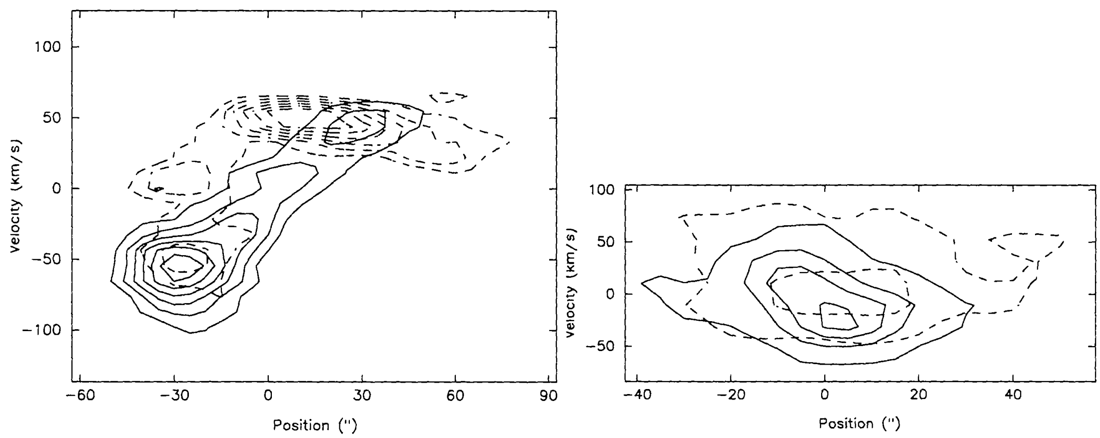

Figure 2. H I position–velocity diagrams towards the tidal tails of Arp 105 (left) and Arp 245 (right). Two components have been identified and disentangled using cuts made at different positions along the tails: one component is associated with gas following a streaming motion along the tail (dashed contours), and a second one which appears to be kinematically decoupled (full contours) and which coincides spatially with the optical tidal dwarf galaxy. Adapted from Duc et al. (1997), and Duc et al. (2000).

disks, whereas another part has been formed *in situ*. Reconstructing the star formation history of a galaxy using for instance its color-magnitude diagram might reveal a tidal origin. These methods have already been used to identify some older TDG candidates, both in the field as well as in clusters (Hunter, Hunsberger, & Roye 2000; Duc et al., in prep.). But so far, the overall fraction of dwarf galaxies of tidal origin remains unknown.

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DISCUSSION:

James Higdon: Two questions: (1) Have you actually measured the metal abundances in the TDGs, and if so what values do you find? (2) Could star formation in the TDGs make a significant contribution to the observed abundances?

Pierre-Alain Duc: The mean oxygen abundance so far measured in the H II regions of TDGs is one-third of solar. Given the young age of TDGs — 100 Myr for some of them — it is unlikely that a strong local enrichment due to in situ star formation could have occured. Besides, the measured metallicity is roughly that of the outerskirts of spirals from which the building material of TDGs originates. Therefore the abundance simply reflects the tidal origin.

John Hibbard: This is a question for Josh Barnes and Chris Mihos: in Arp 105 and Arp 245, most of the tidal starlight and H I is actually associated with the putative TDGs, rather than the tails in general. In the simulations I have seen, the dwarf-like clumps appear small (relative to the thickness of the tails), and contain a small fraction of the total tidal material. Have Josh or Chris run any simulations in which the clumps can grow to the sizes observed in the two systems mentioned above?

Chris Mihos: Not really. Typically the biggest clumps which form in the simulations have gas masses of a few $\times 10^8\,M_\odot$ and comprise maybe 10–20% of the tidal tail gas. Not nearly as extreme as what is seen in Arp 105 or Arp 245. Even in models with more extended gas disks and where the gas is allowed to cool to temperatures of a few thousand degrees, the clumps are not as extreme as what is seen in these two systems.

Pierre-Alain Duc: In our own simulations of the interacting system Arp 245 (Duc et al. 2000), we do not produce in the tidal tails an object as massive as the TDG Arp 245N. This is perhaps due to a lack of resolution and the use of inadequate thermodynamic prescriptions, in particular a cut-off of the cooling function.

Josh Barnes: I'd agree that the dwarfs produced by gravitational instability are small compared to the *width* of the tails, though perhaps not compared to their thickness. Reducing the dispersions of the initial disks increases the fraction of tail material in dwarfs, but it does not easily explain why most of the material is clumped into a very few objects (if that's an accurate description of the TDG Arp 245N). I would expect improving the resolution and/or allowing the gas to cool further would have similar effects; i.e., increasing the yield of *small* dwarfs rather than driving most of the material into a few *larger* dwarfs. To turn most of a tail into (for example) just one object would require very special initial conditions; i.e., some sort of overdensity in the victim disk which could collapse as soon as it was extracted from it's parent galaxy's tidal field.

Terry Romero and Helen Sim