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Letter to the Editor

The large extent of dark matter haloes probed by the formation of tidal dwarf galaxies

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Abstract. In several interacting systems, gas accumulations as massive as 10^9 $M_\odot$ are observed near the tip of tidal tails, and are thought to be possible progenitors of Tidal Dwarf Galaxies. Using N-body simulations of galaxy interactions, we show that the existence of such features requires that dark matter haloes around spiral galaxies extend at least ten times further than the stellar disks. The massive gas clouds formed in our simulations have a kinematical origin and gravitationally collapse into dwarf galaxies that often survive for a few billion years.

Key words. galaxies: formation, evolution, interactions, haloes

1. Introduction

Dark matter haloes are known to surround galaxies, but whether they extend much further than visible matter is still debated. Standard cosmological models based on Cold Dark Matter theories predict that the dark halo of a galaxy should extend and maintain large circular velocities up to its virial radius, that is about 200 kpc for a galaxy of the mass of the Milky Way (Navarro et al. 1996). This result is yet difficult to check by observations. Rotation curves of spiral galaxies can shed light on dark matter (DM) only at small radii and in the disk plane. At larger distances, on may however take advantage of the special location or morphology of some peculiar systems to probe the dark matter distribution. The kinematics of polar rings can give information on the flattening of dark haloes (Iodice et al. 2003). The morphology of the long tidal tails (Springel & White 1999; Dubinski et al. 1999) and the distribution and kinematics of satellite galaxies (Zaritsky & White 1994; Erickson et al. 1999; Ibata et al. 2001) can be used to constrain the shape of dark haloes. Finally one may study the internal dynamics of Tidal Dwarf Galaxies (TDG) – gravitationally bound objects formed out of tidal material (Duc et al. 2000) – to probe their baryonic DM content and learn whether part of the latter could originally have been located in a galactic disk (Braine et al. 2001).

In this letter, we show how the very existence of large accumulations of gaseous tidal material, progenitors of massive TDGs, can put some constraints on the large-scale extent of dark matter haloes. HI gas clouds with masses higher than 10^9 $M_\odot$ are observed in the outer parts of the long tidal tails emanating from several nearby interacting systems (e.g. Hibbard & van Gorkom 1996; Duc et al. 1997, 2000; Nordgren et al. 1997; Braine et al. 2001)[1]. These clouds are usually real entities and not the results of projection effects. Indeed, they are able to convert their neutral hydrogen into molecular gas (Braine et al. 2001), form stars and may evolve into objects that have the apparent properties of dwarf galaxies.

The formation of TDGs has been studied in numerical simulations showing the gravitational collapse of stellar clumps in tidal tails (Barnes & Hernquist 1992), or the ejection of gas clouds from the parent galaxy (Elmegreen et al. 1993). These objects have masses of 10^7 to 10^8 $M_\odot$ and are distributed all along the tails like the TDG candidates found in numerous interacting systems (Weilbacher et al. 2000). However, the most massive TDG progenitors located near the tip of the tidal filaments have not yet been reproduced in these simulations.

We present here new numerical simulations that aim at exploring two issues: (1) how do HI clouds as massive as 10^9 $M_\odot$ form in tidal tails? (2) are such clouds transient features that quickly fall back into their parent galaxy, or are they the progenitors of long-lived objects able to contribute significantly to the overall population of dwarf galaxies and have a cosmological importance (Hunter et al. 2000; Okazaki & Taniguchi 2000)? We will show that the answers to these questions also shed some light on the DM haloes of galaxies.

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[1] See also in the HI Rogues Gallery (Hibbard et al. 2001) the collection of interacting doubles (available at http://www.nrao.edu/astrores/HIrogues/).

2. Numerical simulations

2.1. Code and models

We used N-body simulations of galactic encounters and mergers in order to study the response of gas to tidal interactions. The target galaxy consists of 50 000 particles describing the stars, 100 000, the dark matter, and 100 000 sticky ones, the gas. Its stellar disk has a 15 kpc radius, and is modeled by a Toomre disk with a scale-length of 7 kpc and a vertical scale-height of 1 kpc. Its gaseous disk has a radius of 2.3 times the stellar disk radius. The gas mass is a few 10^9 to 10^{10} $M_{\odot}$ and the total luminous mass is 2×10^{11} $M_{\odot}$. The second galaxy is gas free in our simulations, while in reality it may contain some gas. However, this does not affect our results since the tidal tails of one galaxy are not disturbed by the gas present in the other one, except in very particular situations. The dark matter is described as a standard isothermal sphere. For each galaxy, its distribution is computed to provide a flat rotation curve inside the halo truncation radius, which we chose between 3 and 10 times the stellar disk radius. We also explored a range of mass ratios, relative velocities and impact parameters for the colliding galaxies. The characteristics of our different runs are listed in Table 1.

The gravitational potential of stars and dark matter is computed via the three-dimensional FFT code presented in details in Bournaud & Combes (2003). Using dark haloes as extended as 150 kpc compels us to explore a large region, hence reducing the resolution of this 3D code to about 5 kpc. This resolution is large enough to compute the potential of stars and dark matter in which the gas response is studied, but is too low to reproduce the gas self-gravity inside the tails. We have therefore limited our study to coplanar galactic encounters, in which gas forms thin structures included in a plane. This enables the gas gravitational potential to be computed with a two-dimensional FFT code having a much higher resolution of about 150 pc (Bournaud & Combes 2002). Once potentials are known, equations of motion are integrated by a leap-frog algorithm. The dissipative nature of the interstellar medium is described using the sticky-particles algorithm of Bournaud & Combes (2002).

2.2. Results

In our first model presented in Fig. 1, dark matter haloes do not extend much further than visible matter (stars and gas). Galaxy interaction makes a tidal tail develop, in which more than ten regions collapse under the effects of gravity. This result is very similar to what was obtained in previous simulations (e.g., Barnes & Hernquist 1992): bound clumps of 10^7 to 10^8 $M_{\odot}$ are formed all along the tails. This model fails to reproduce the most massive gas accumulations seen in real systems. Even with varying the galaxies mass ratio, orbital parameters, and the initial extent and distribution of gas, such structures are never formed.

Figure 2 presents a second model where the dark haloes extend up to 10 times the radius of the stellar disk. The small tidal clumps obtained with the first model are still there but, in addition, objects of 10^9 $M_{\odot}$ may form in the outer parts of tidal tails (see Fig. 3). They are actually produced in most of our runs (see Table 1), *provided that (1) long tidal tails are formed (2) the extent of haloes is at least a factor of ten greater than the radius of the stellar disks.* The long-lived tidal objects remain at more than 50 kpc from the galaxy center for at least 2 Gyr after their formation.

Table 1. Parameters of the simulated collisions. M is the mass ratio (disturbed galaxy to disturbing galaxy), V the relative velocity at large distance (in km s^{-1}), and b the impact parameter (in kpc). The last column indicates whether, for simulations with a large DM halo truncation radius, massive TDGs were formed or not. In all these runs, orbital parameters are chosen to allow large tidal tails to develop. In particular the orbits of the galaxies were prograde.

Run	M	V	b	Results for extended DMHs
1	1	55	90	2 massive TDGs
2	2	55	90	1 massive TDG
3	3	55	90	no massive tidal object
4	0.5	55	90	1 massive TDG
5	0.25	55	90	1 massive TDG
6	1	30	90	1 massive TDG
7	1	80	90	2 massive TDGs
8	1	125	90	no massive tidal object
9	1	55	65	2 massive TDGs
10	1	55	120	1 massive TDG
11	1	55	150	1 massive TDG

3. Discussion and conclusions

3.1. Implications on dark haloes

Experiments probing the shape of dark matter haloes using the kinematics of satellite galaxies led to somehow conflicting results (Zaritsky & White 1994; Erickson et al. 1999) and to the suggestion that it was perhaps not universal. The massive and extended dark matter haloes used in standard CDM cosmologies have also been challenged by the ability of colliding galaxies to form long tidal tails (Mihos et al. 1998). In the N-body simulations by Springel & White (1999), however, the more extensive haloes make stronger tails.

Our simulations indicate that the existence of very massive HI accumulations in the outer parts of tidal tails, once formed, cannot be accounted for with isothermal dark haloes that are truncated at small radii, whatever the other physical parameters used in the simulations are. On the contrary, they are reproduced in most runs when the dark haloes of both interacting galaxies are assumed to extend much further than the visible matter, at least 10 times or 150 kpc for a galaxy of the mass of the Milky Way. The critical parameter for the TDG-production ability is the halo size, not its mass. Indeed, we have run a set of simulations with haloes truncated at three times the stellar disk radius but as massive as in the second model. They all failed at producing massive tidal clouds.

3.2. Formation and survival of tidal dwarf galaxies

The formation of bound star-forming clumps along tails is directly related to gravitational instabilities in tidal structures

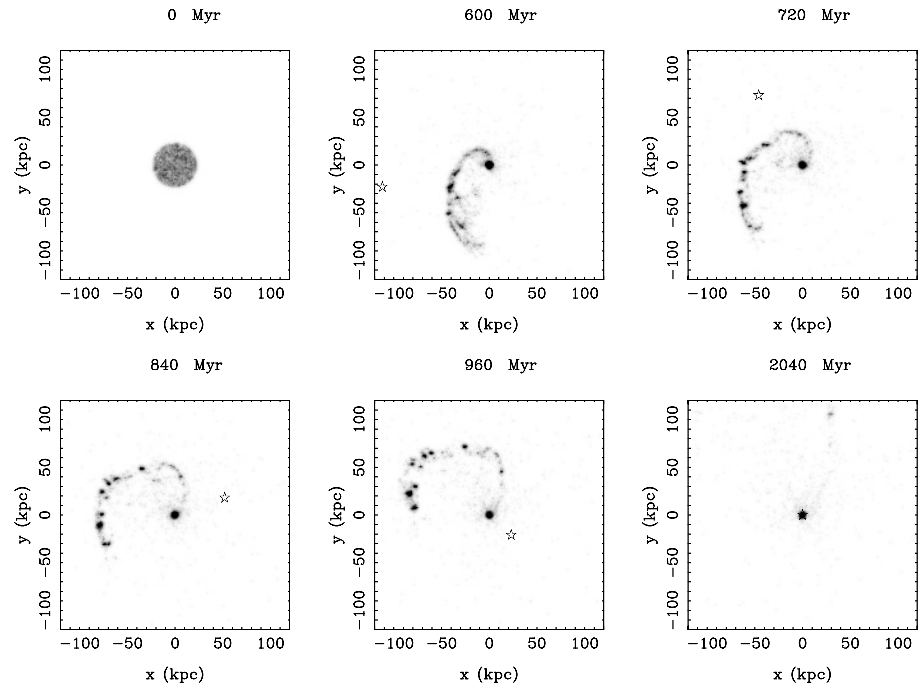

Fig. 1. Response of the gaseous disk of a galaxy to a tidal interaction. The collision parameters are those of run 2 (see Table 1). Dark haloes are initially truncated at three times the optical radius of the galaxies. The gas column-density is plotted in grayscale. The center of the second galaxy is represented by the star symbol. More than ten gravitational clumps collapse along the tail with masses of 10^7 to 10^8 $M_{\odot}$.

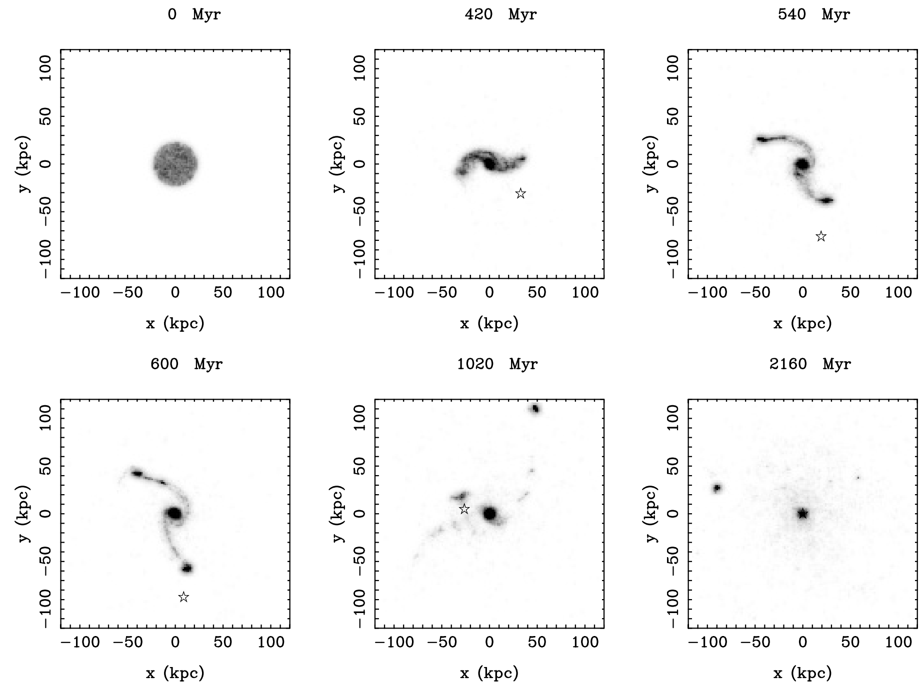

Fig. 2. Same run as in Fig. 1, with the truncation radius of the dark haloes extended up to 10 times the radius of the stellar disks. Gas accumulations of 10^9 solar masses are formed at the tip of each tidal tail. One of them quickly falls into the disturbing galaxy, while the other one forms a gravitationally bound object that orbits at large radii on a nearly circular path.

(Barnes & Hernquist 1992). They are the progenitors of super star clusters and possibly to dwarf spheroidal galaxies (Kroupa 1998).

The more massive gas accumulations near the tip of the tidal tails – those only obtained with extended dark haloes – seem to have a different origin. Indeed, they are still observed in simulations where the gas is not self-gravitating. Thus, these structures are not initiated by self gravity but are firstly the result of a kinematical phenomenon. For parent galaxies having both an extended halo, tidal forces make a significant fraction of the gas coming from beyond a critical distance in the parent's disk to pile up near the extremity of the tail, whereas for a truncated halo, the gas is spread all along the tail. Once enough material has accumulated, self-gravity leads to a local collapse and ignites the star formation. A more detailed investigation will be published in a forthcoming paper.

The survival time of these TDGs will be determined by its ability to resist tidal disruption, internal starbursts, or an eventual merging with the parent galaxy. In our simulations, although much of the tidal material along the tails falls back in less than 1 Gyr, the tidal dwarf galaxies that are formed at radii larger than 50 kpc are still observed after 2 Gyr. One third of them remain on orbits that are almost circular (see Fig. 2) and hence appear as satellite galaxies. Due to their low

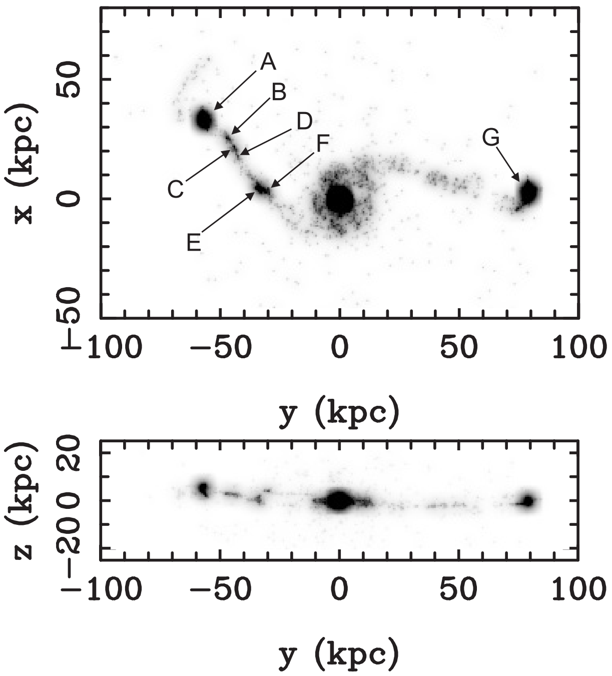

Fig. 3. Same run as in Fig. 2 observed at $t = 600$ Myr. The initial disk plane is seen face-on (top) and edge-on (bottom). Two tidal dwarf galaxies (A and G) are formed near the extremity of the tails, with respective masses of 1.1 and $1.3 \times 10^9\ M_\odot$. The smaller gravitational clumps distributed along the tails (B to F) have masses from $3\times10^7\ M_\odot$ to $11 \times 10^7\ M_\odot$. The initial gas mass in the disk was $10^{10}\ M_\odot$.

eccentricities, the final merging is postponed (Peñarrubia et al. 2002) and their life-time is increased. Therefore such tidal dwarf galaxies cannot be considered as transient objects. Old TDGs should exist (Hunter et al. 2000) and could actually represent a significant fraction of the dwarf galaxies present in nearby groups of galaxies, as suggested by Hunsberger et al. (1996) or in the distant Universe, as speculated by Okazaki & Taniguchi (2000).

We have restricted our study to coplanar encounters in order to treat the gas self-gravity with a large enough resolution. Since we found that the origin of the large tidal gas accumulations is not the self-gravity, we have run a set of numerical experiments with non-coplanar encounters in which the gas is simply modeled by mass-less particles. The piling-up of gas near the tail extremities still occurs only when dark haloes are extended enough. The constraint on the size of dark haloes derived from the simulations appears therefore to be robust. On the observational side, statistics of the number, location, masses and ages of TDGs need to be accumulated.

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