Mapping the Hidden Universe: The Universe Behind the Milky Way - The Universe in HI
ASP Conference Series, Vol. 218, 2000
R.C. Kraan-Korteweg, P.A. Henning, and H. Andernach, eds.

Tidal Dwarf Galaxies in the Interacting System NGC 2992/2993

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Abstract. We present multi–wavelength results and numerical simulations of the interacting system NGC 2992/2993 (Arp 245). This pair is composed of two colliding spiral galaxies out of which emanate long stellar tails and a bridge. H II regions are observed at the end of one of the stellar tails at the location of an object classified as a tidal dwarf galaxy. Our spectacular VLA H I map reveals a huge intergalactic ring associated with NGC 2993 and a long tidal tail escaping from NGC 2992 coinciding with the optical one, with at its tip a massive clump that hosts most of the atomic gas in the system. The latter is associated with the star–forming tidal dwarf. Unlike the tail, most of the H I ring has no stellar counterpart.

Although NGC 2992/2993 is quite exceptional, it has a morphology that has been fairly successfully modelled, reconstructing the history of the collision. Refinement of this model should allow us to date the onset of the various phenomena observed in this system, making it a test case for studying the effects of interactions on galaxy evolution.

1. Introduction

The field of galaxy interactions is enjoying an ever increasing popularity, as a cursory survey of the literature will immediately reveal. A recent review of the field is given by Struck (1999). In addition to the usual "destruction" of two galaxies involved in the interaction and eventual merging, there is ample evidence for the creation of dwarf galaxies in the process. Zwicky (1956) already speculated that as a result of the interaction, fragments can be ejected. This idea of recycling of material was in turn mentioned by Schweizer (1978) in the case of the interacting system NGC 4038/39, but it was only after papers by Mirabel et al. (1991, 1992) that interest in tidal dwarf galaxies, objects formed out of the debris of a tidal interaction, took off.

Detailed H I maps of a number of interacting systems (e.g., Hibbard & van Gorkom 1996, Kaufman et al. 1997, and references therein) have shown that a large fraction of the gaseous component of colliding galaxies can be expelled into the galactic halos or even into the intergalactic medium as a result of tidal forces. In some systems, up to 90% of the atomic hydrogen is observed outside the optical disk like in Arp 105 (Duc et al. 1997). Some of this gas might recondense within the halo of the merger and form a new generation of galaxies: tidal dwarf galaxies (TDGs; see the review by Duc & Mirabel 1999).

TDGs are often found at the tip of tidal tails at distances between 20 and 100 kpc from the merging objects, of which at least one should be a gas-rich galaxy. They themselves are gas-rich objects that can be as massive as the Magellanic Clouds, form stars at a rate which might be as high as in blue compact dwarf galaxies (BCDGs) and seem dynamically independent from their parent galaxies.

Arp 245, an interacting system consisting of two spiral galaxies, NGC 2992 and NGC 2993, appears to be an interesting testcase as it can be fairly easily modelled. Moreover, it is a relatively nearby system, at an adopted distance of 31 Mpc[1]. Its prominent tidal tails host a tidal dwarf galaxy candidate which, because of its proximity, can be studied in detail.

2. H I Observations

We performed H I observations with the NRAO[2] Very Large Array (VLA) at an effective spatial resolution of $19'' \times 14''$ and a velocity resolution of $21\,\mathrm{km\,s^{-1}}$. Figure 1 shows the H I surface density map as contours overlaid on an optical V-band image.

The H I surface brightness map shows several stunning features. First of all, three galaxies were detected, the interacting pair NGC 2992/2993 plus a third galaxy, an edge-on dwarf catalogued as FGC 0938 (Karachentsev et al. 1993), which does not seem to be involved in the interaction given the fact that even

[1]based on $H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$; at the distance of Arp 245, $1'$ corresponds to 9 kpc.

[2]The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

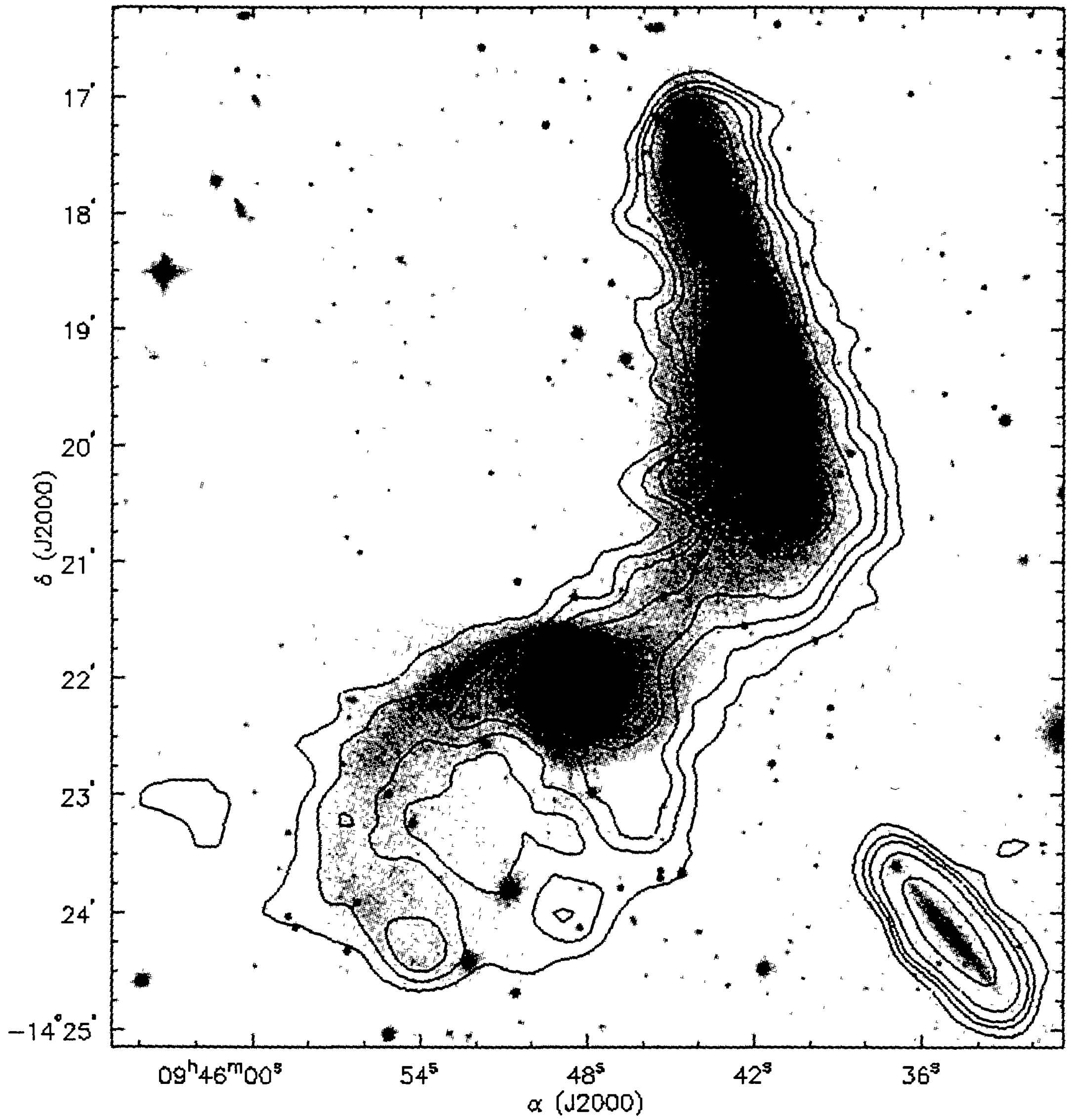

Figure 1. H I distribution of Arp 245 superimposed as contours on a V–band optical greyscale image. The H I data were smoothed to a circular 25″ beam. Contour levels are drawn at 1, 2, 3, 5, 10, and 20×10^{20} cm^{-2}. NGC 2993 is the bright object just to the south of the centre; NGC 2992 is the other large object to the middle right which is connected to the former by an H I bridge. The Tidal Dwarf Galaxy is the object at the tip of its northern tidal tail. At the same redshift, but apparently not participating in the interaction, we detected a gas–rich, edge–on dwarf galaxy known as FGC 0938 (bottom right hand corner).

its outermost contours seem completely undisturbed. Its redshift is only slightly higher, by some 125 km s^{-1} with respect to the interacting pair.

A 50 kpc H I tail stretches from NGC 2992 to the north, ending at its tip in what we claim is a Tidal Dwarf Galaxy (TDG). H I is also found in the bridge region between both interacting galaxies and in a huge, ring–shaped tidal feature to the south–east of NGC 2993. On optical images, stellar counterparts to the northern tail, bridge, and the eastern part of the tidal arm torn from NGC 2993 can easily be detected. However, not even on our deepest optical images do we see any sign of a stellar counterpart to the southern part of the H I ring feature.

The mass in H I in the northern tidal tail constitutes some 60% of the H I belonging to NGC 2992. The tidal features, including the H I ring belonging to NGC 2993 add up to 80% of the total H I budget. Column densities in the H I ring are everywhere below $3 \times 10^{20}\,\mathrm{cm}^{-2}$, thought to be too low for star formation to take place. Column densities at the location of the TDG where star formation does occur reach $2 \times 10^{21}\,\mathrm{cm}^{-2}$ (see below).

3. Numerical Simulations

We developed a first, approximate model of the interaction, exploring the parameter space for finding the most likely orbit and fine–tuning it somewhat in order to try to explain the most obvious features. The prominence of the tails suggests a prograde encounter. For simplicity, we assumed that NGC 2993 is seen face–on. We used fully self–consistent simulations with the Tree–SPH code GADGET. Cooling of the gas, star formation, and feedback were taken into account as in Springel (2000). We used 60000 particles to represent the Dark Matter, 40000 for the stellar disk, 10000 for the bulge and 40000 for the gas.

The orbit is assumed to be initially parabolic. It takes 1 Gyr after the DM haloes touch for the first time, for the interacting galaxies to reach perigalacticon. At a time 100 Myr later we find excellent correspondence between the model and our observations, both in their morphology as well as in the velocity distribution across the interaction. We predict, based on our models that the galaxies, after separating, will fall back again about 700 Myr after their first, dramatic collision and will merge within a further 100 Myr to form one merger remnant. Figure 2 shows a time sequence of the simulations.

4. The Tidal Dwarf Galaxy Arp 245N

Arp 245N, the bright object located at the tip of the tidal tail emanating from NGC 2992, shows many of the characteristics of a forming tidal dwarf galaxy. An image in the light of Hα shows that active star formation is taking place (see Figure 3). As the ages of the young stars are below 50 Myr and the time for stars to move from the parent spiral galaxy disk out to the tip of the tail is at least a factor of 4 larger, star formation has to be taking place *in situ*. This notion is enforced by the recent detection by Braine et al. (2000) of CO(1–0) and CO(2–1) at the location of the TDG.

A TDG is made up of a mix of older stars, tidally pulled out of the parent system and young stars, formed locally. Using our broad–band BVRJHK data we estimated a contribution of young stars of less than 2% of the overall

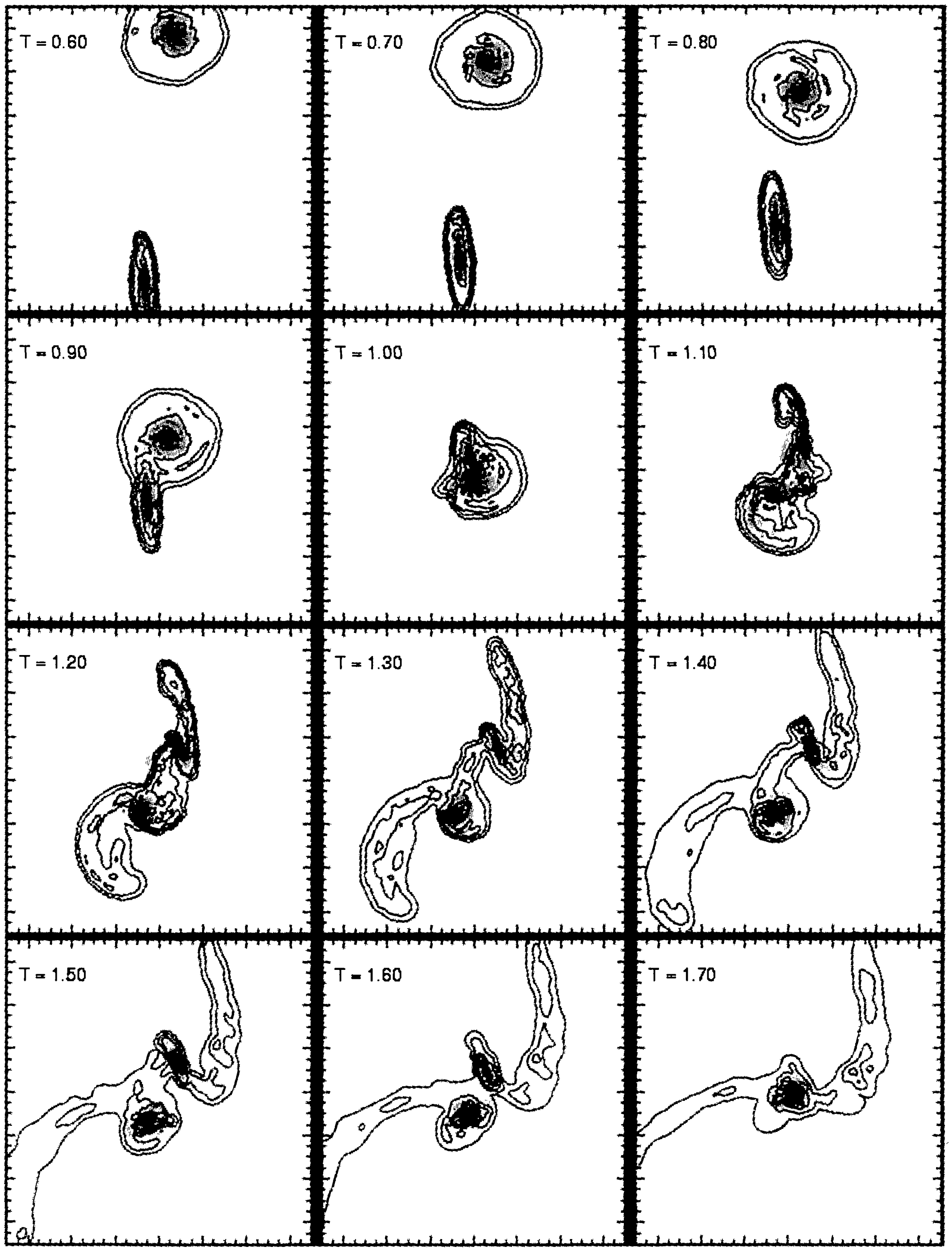

Figure 2. Time evolution of the numerical model simulating the interaction of the system Arp 245. Shown here are the stars (grey scale) and gas (contours). Each panel measures 140 kpc across. Times are in Gyr after first contact of the DM haloes. Perigalacticon is at T=1.0 Gyr; T=1.1 Gyr corresponds best to the current observed morphology. The three-dimensional model has been projected on to the sky plane to coincide with the current relative orientation of the galaxies.

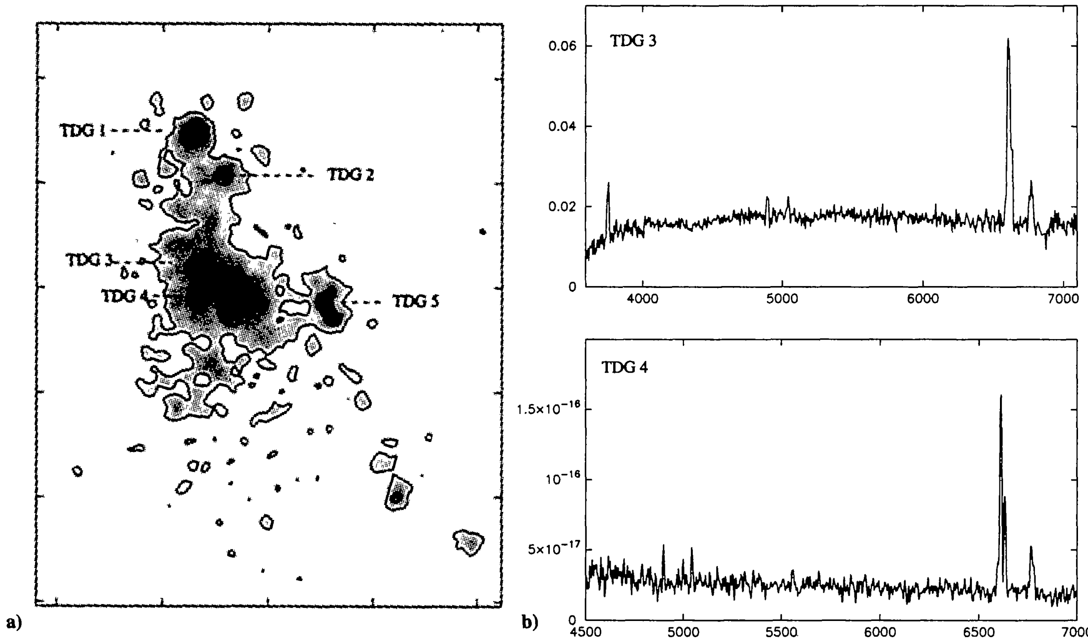

Figure 3. (a) Hα map of the Tidal Dwarf Galaxy Arp 245N. Five distinct H II regions are indicated. Contour levels are at 10, 30, 50, 70, and 90% of the peak flux of 4×10^{-16} erg s^{-1}. The interval between tick marks is 10″. (b) Long–slit optical spectra of TDG 3 (arbitrary units) and TDG 4 (units in erg cm^{-2} Å^{-1}) which are typical of H II regions.

stellar mass of the TDG. The current star formation rate, corrected for internal extinction, is at most 0.13 M$_{\odot}$ yr^{-1}.

Long–slit spectra which we obtained as well show that the heavy element abundance is of order 1/2 solar, close to that found in the interstellar medium at the outskirts of spiral galaxies and much higher than that found on average in isolated (field) dwarf irregular galaxies. It is, of course, this gas at large radial distance which is most easily drawn out to form tidal tails.

5. Summary

The interacting system Arp 245, consisting of the galaxies NGC 2992/2993, is in the process of spawning a tidal dwarf galaxy, Arp 245N. Based on our multi–wavelength study of this system we derive the following results:

1. A preliminary numerical simulation suggests that we observe the system some 100 Myr after first encounter (perigalacticon) and that the system will merge in another 700 Myr.

2. The gas, as traced by H I, is tidally drawn out to as far as 50 kpc. About 60% of the gas formerly belonging to NGC 2992 and almost 80% of the gas of NGC 2993 are found in tidal features: the tail north of NGC 2992, a bridge of gas connecting both galaxies, and a giant loop to the southeast.

3. Our H I maps show at the same redshift, and hence distance, an edge–on dwarf galaxy, FGC 0938, which seems undisturbed.

4. At the tip of the northern tidal tail we find a concentration of stars and gas and ongoing star formation, as evidenced by broad–band and Hα CCD imaging and optical long–slit spectroscopy. This finding is compatible with the formation of a TDG out of the tidal debris.

5. For the first time CO has been detected in a TDG candidate (Braine et al. 2000), supporting the idea that conditions in the TDG candidate resemble that in field dwarf irregular galaxies.

A more complete account of our results has been accepted for publication (Duc et al. 2000).

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