Dwarf Detachment and Globular Cluster Formation in Arp 305

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Abstract. Tidal Dwarf Galaxies (TDG), concentrations of interstellar gas and stars in the tidal features of interacting galaxies, have been the subject of much scrutiny. The ‘smoking gun’ that will prove the TDG hypothesis is the discovery of independent dwarf galaxies that are detached from other galaxies, but have clear tidal histories. As part of a search for TDGs we are using GALEX to conduct a large UV imaging survey of interacting galaxies selected from the Arp Atlas. As part of that study, we present a GALEX UV and SDSS and SARA optical study of the gas-rich interacting galaxy pair Arp 305. The GALEX UV data reveal much extended diffuse UV emission and star formation outside the disks including a candidate TDG between the two galaxies. We have used a smooth particle hydrodynamics code to model the interaction and determine the fate of the candidate TDG.

1 INTRODUCTION

The so-called ‘Tidal Dwarf Galaxies’ (TDG), concentrations of interstellar gas and stars in the tidal features of interacting galaxies that may become independent dwarf galaxies, have been the subject of intense scrutiny (e.g., Bournaud & Duc 2006; Recchi et al. 2006; Duc, Bournaud, & Boquien 2006). The ‘smoking gun’ that will unambiguously prove the TDG hypothesis is the discovery of independent dwarf galaxies that are detached from other galaxies, but have clear tidal histories.

As part of a search for TDGs and to study star formation in tidal features, we have used the Galaxy Evolution Explorer (GALEX) telescope (Martin et al. 2005) to conduct a large UV imaging survey of interacting galaxies selected from the Arp (1996) Atlas. We have found a number of previously unstudied candidate TDGs in our sample (Smith et al. 2009, also see B. Smith et al., this conference proceedings).

In this proceedings we present results from Hancock et al. (2009) on the interacting galaxy pair Arp 305 (NGC 4016/7). We have obtained UV and optical images of Arp 305 from the GALEX, Sloan Digitized Sky Survey (SDSS), and the Southeastern Association for Research in Astronomy (SARA) telescopes.
2 DISCUSSION

2.1 Morphology and General Properties

Arp 305 is a very wide pair with the primary galaxy, NGC 4017, to the South and the companion, NGC 4016, to the North. NGC 4017 appears nearly face-on, with two tidal tails, one pointing northwest and one to the southeast. The UV images show much extended emission to the northwest and southeast far outside the main disk (Hancock et al. 2009). The primary seems to have an ocular waveform, a bright oval of star formation shaped like an eyelid (e.g. Kaufman et al. 1997; Hancock et al. 2007; Elmegreen et al. 2006)

The Northern galaxy, NGC 4016, shows a misshapen bulge with a dusty disk. In the inner disk, a curious figure-eight shape is seen (Hancock et al. 2009). We suspect that the figure-eight formation is the result of a bar (see the third frame of Figure 3 in Romero-Gómez et al. 2008).

Elmegreen, Kaufman, & Thomasson (1993) noted that this galaxy pair showed scattered debris resembling dwarf galaxies. The most prominent debris is seen in a partial residual bridge between the two spiral galaxies. This feature is particularly striking in the GALEX images (Figure 1). For simplicity, we will adopt the name ‘bridge TDG’ for the tidal dwarf candidate in the residual bridge. With SARA, we have detected Hα emission from this feature confirming that it is at the same redshift as the galaxies. This structure is clearly detected in HI (van Moorsel 1983), further suggesting that it is part of the Arp 305 system.

2.2 Reddening and Ages

We have identified 45 star forming clumps in Arp 305 from the GALEX FUV images. The bridge TDG contains four of these clumps (Figure 1). Two additional detached TDG candidates northeast and southwest of NGC 4016 are also marked in Figure 1.

To estimate the ages of the star forming clumps we compared various color combinations to sets of Starburst99 (SB99) models (Leitherer et al. 1999). See Hancock et al. (2003) for details on the SB99 models and the age determinations.

We do not see any old clumps in this system in spite of the fact that the last closest encounter was about 300 Myr ago. Perhaps this is the result of cluster dissolution or the so called cluster ‘infant mortality’ (e.g. Peterson et al. 2009; Bastian 2005; Fall, Chandar, & Whitmore 2005). However, this could be a selection effect. We selected the clumps from the FUV image so have chosen the youngest clumps. Another possibility is our limited resolution. It is likely that the clumps are made up of several unresolved clusters and/or associations. The light in our photometric apertures would be dominated by the younger clusters.

The absence of intermediate age clumps in the tidal structures of Arp 305 and some other systems (e.g. Arp 82 and Arp 285; Hancock et al. 2007; Smith et al. 2008) indicates that it is difficult to make long-lived TDGs.

2.3 The Bridge TDG

The bridge TDG looks to be embedded in a massive HI plume stretching North from the primary (van Moorsel 1983). The stars in the bridge TDG most likely formed in situ. The distance between the nucleus of the primary and the bridge
TDG is $\sim 36$ kpc. The clumps in the bridge TDG are an average of 19 Myr old. To travel 36 kpc in 19 Myr the material would have to travel at a velocity of roughly $2000 \text{ km s}^{-1}$ relative to the primary. The HI kinematics do not support this (van Moorsel 1983).

We estimate that the combined stellar mass for the clumps in the bridge TDG is $\sim 1 - 7 \times 10^6 M_\odot$. These clump masses are consistent with that of Galactic globular clusters (e.g., Pryor & Meylan 1993) and Super Star Clusters (SSC) (e.g., Holtzman et al. 1992, 1996; O’Connell, Gallagher, & Hunter 1994; Schweizer et al. 1996; Whitmore et al. 1993; Whitmore & Schweizer 1995; Watson et al. 1996). For comparison, the TDG candidates in Higdon, Higdon & Marshall (2006) have stellar masses around $2 \times 10^7 M_\odot$ to $3 \times 10^8 M_\odot$.

The HI mass of the bridge TDG is $\sim 6 \times 10^7 M_\odot$ consistent with the 29 low mass dwarfs studied in Begum et al. (2008) ($10.18 - 81.14 \times 10^6 M_\odot$). The HI mass/luminosity ratio for the bridge TDG is $M_{HI}/L(B) \sim 1 M_\odot/L_\odot$, similar to those of irregular and compact blue dwarfs (e.g., Hunter & Elmegreen 2004; Pisano et al. 2005; Tarchi et al. 2005; Begum et al. 2008). The bridge TDG has an $H\alpha$ luminosity of $3.2 \times 10^{38} \text{ erg s}^{-1}$, similar to the $H\alpha$ luminosities of the dwarfs in Hunter & Elmegreen (2004) and the tidal features studied by Smith & Struck (2001).

### 2.4 Other Clumps of Interest

There are two other TDG candidates in Arp 305. To the southwest of NGC 4016 is a bright clump (Figure 1), that appears to be at the tip of a faint tidal arm. This clump is bright in both the GALEX UV and all the SDSS optical bands and is within the extended HI envelope (van Moorsel 1983). It is not detected in our continuum subtracted $H\alpha$ images. This TDG candidate is the oldest clump in our sample. We cannot rule out the possibility that this object is a foreground star or a background object.

To the northeast is another possible TDG. The northern tail of NGC 4016 points toward this clump. This TDG candidate is also bright in both the GALEX UV and all the SDSS optical bands, and is not detected in our continuum subtracted $H\alpha$ images. Figure 1 shows this northern TDG candidate to be an extended object with an appearance similar to an inclined disk. Given this, the lack of an $H\alpha$ detection, and the large distance from NGC 4016 ($\sim 70$ kpc), we can not rule out the possibility that this is a background galaxy.

Near the bases of both the northeastern and southwestern tidal tails in NGC 4017 are extremely luminous clumps. These ‘hinge clumps’ likely form when material is pulled out from deeper in the original disk. This material, gas with higher initial densities, is more compressed. Moreover, being pulled out in a tail likely reduces the shear levels of the original disk, allowing self-gravity to more easily form big clouds. The ‘hinge clumps’ are the two brightest UV clumps in the primary and are very bright in $H\alpha$. A luminous ‘hinge clump’ was also observed in Arp 82 at the base of the long extended northern tail (Hancock et al. 2007).

### 2.5 SPH Model of the Encounter

What is the long term fate of the clusters that do survive, and do any of those that might represent TDGs detach in some sense? We have investigated those
questions by running numerical simulations. We used the SPH code of Struck (1997). This code was also used to model other systems recently (e.g., Arp 284, Struck & Smith 2003; IC 2163/NGC 2207, Struck et al. 2005; Arp 107, Smith et al. 2007; Arp 82, Hancock et al. 2008; and Arp 285, Smith et al. 2008).

The TDG particle in Figure 2 turned on SF at a time and place like that of the bridge TDG in the observations, and might illustrate the fate of the bridge TDG. If so, that fate is to be captured by the companion and carried into the merger. It seems very unlikely that TDGs formed in the bridge will detach and survive the merger.

The models suggest the eventual merger is about 1.3 Gyr from the time depicted in Figure 2. The bridge TDG could persist for this long, consistent with recent results. In their extensive N-body study of tidal dwarf formation Bournaud & Duc (2006) found that 75% of the dwarf candidates fell back into the galaxies within a few $\times 10^8$ yr. The remaining 25% had a typical lifetime of more than 2 Gyr. Most of the later formed in the outer parts of tidal tails. However, we are not sure if the bridge TDG is currently bound. We don’t know whether it will survive the first and subsequent fall backs.

3 SUMMARY

We present results from Hancock et al. (2009) on the candidate TDGs in the interacting galaxy pair Arp 305 (NGC 4016/7). A prominent TDG candidate is seen in a partial residual bridge between the two spiral galaxies. We summarize the bridge TDG analysis below:

- Mean Age ~ 19 Myr, E(B-V) ~ 0.06
- Stars formed in situ
- Total Stellar Mass of the 4 clumps ~ $1 - 7 \times 10^6 M_\odot$
- Total HI Mass ~ $6 \times 10^7 M_\odot$
- Mass more similar to SSCs or perhaps a small TDG
- Has a clear tidal history
- It is not clear if the TDG is a single bound object
- Unlikely to permanently detach and survive the merger
- Could persist for ~ 1.3 Gyr

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Figure 1. GALEX FUV images of Arp 305. Left: NGC 4017 with the bridge TDG circled. Right: NGC 4016 with two candidate TDGs circled. North is up and East is to the left. See Hancock et al. (2009) for color images with scale bars.

Figure 2. Illustration of the orbital trajectory of star-forming particles from the onset of star formation in the bridge to the end of the run when the galaxies have merged, over-plotted on the gas particle distributions at a selected time in the interaction. Dots show the locations of gas particles, at the time of SF onset in the selected particles. Black circles show the position of the companion center at selected time-steps from closest passage to merger. The asterisk shows star-forming particles in selected tidal structures, i.e. the TDG. The curve shows the particle trajectory from the onset of SF to the end of the run when the two galaxies have merged.