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ULTRAVIOLET MORPHOLOGY AND STAR FORMATION IN THE TIDAL TAILS OF NGC 4038/39

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ABSTRACT

We present *Galaxy Evolution Explorer* far-ultraviolet (1530 Å) and near-ultraviolet (2310 Å) observations of the archetypal merging system NGC 4038/39, "the Antennae." Both tails are relatively bright in the UV, especially in the vicinity of the tidal dwarf galaxy candidates at the end of the southern tail. The UV light generally falls within the optically delineated tails, although the UV light is considerably more structured, with a remarkably similar morphology to the tidal H I. The UV colors suggest that there has been continuing star formation within the tidal tails, even outside the previously studied tidal dwarf regions. Within the inner disk regions, there are interesting UV features that appear to be related to the extended soft X-ray loops and halo recently discovered by *Chandra*.

Subject headings: galaxies: individual (NGC 4038, NGC 4039) — galaxies: interactions — galaxies: ISM — galaxies: starburst — intergalactic medium — ultraviolet: galaxies

1. INTRODUCTION

It has long been known that tidal filaments have blue optical colors, with regions as blue or bluer than the spiral arms of disk galaxies (Zwicky 1956; Arp 1966; Schweizer 1978, hereafter S78; Schombert et al. 1990; Weilbacher et al. 2000). What is not known is whether the blue colors of the tails reflect the fact that they are comprised of formerly star-forming disk material that was ejected from the host spiral galaxies several 10^8 yr ago, or if they reflect ongoing and pervasive tidal star formation.

Localized regions of current tidal star formation have been unambiguously identified via the optical emission lines of the H II regions ionized by young (<10 Myr) stars (e.g., Stockton 1974a, 1974b; S78; Hibbard & van Gorkom 1996; Iglesias-Páramo & Vílchez 2001; Weilbacher et al. 2003). And recently, individual young stars (Saviane et al. 2004) and star clusters (Knierman et al. 2003; Tran et al. 2003; de Grijs et al. 2003) have been discovered within tidal tails. But in general these studies are only sensitive to the youngest objects or only target small regions of the tails. It is thus not clear how prevalent star formation within the tails is, or if star/cluster formation only occurs at specific sites or at a specific evolutionary stage of tidal development.

At a newly revised tip of the red giant branch distance of 13.8 Mpc (used throughout; Saviane et al. 2004), the Antennae is the nearest ongoing major merger and an excellent target for studying tidal star formation. Many studies have concentrated on the spectacular inner regions of this system (e.g., Zhang et al. 2001; Kassin et al. 2003). However, we defer a discussion of those regions to a future paper. Here we concentrate on the tidal regions. We are particularly interested in whether there are widespread stellar populations with ages less than the dynamical time of the tidal tails, which is ~300 Myr as derived from either the maximum tidal extent divided by the maximum tidal velocity (45 kpc/150 km s^{-1}) or the numerical model of Barnes (1988; 320 Myr when scaled to the distance of Saviane et al. 2004).

S78 discovered several H II regions near the end of the southern tail of NGC 4038. Both he and Mirabel et al. (1992, hereafter M92) studied this region and suggested two possible sites of forming or formed "tidal dwarf galaxies" (TDGs): dwarf galaxy–sized self-gravitating objects assembled from tidal debris (e.g., Duc & Mirabel 1999). In the following, we refer to these regions as TDG (S78) and TDG (M92) and indicate their locations in Figure 1 (see also Hibbard et al. 2001). The stellar population of the TDG (M92) region was studied with the *Hubble Space Telescope* (*HST*) Wide Field Planetary Camera 2 (WFPC2) by Saviane et al. (2004), who find a population of eight young stellar associations (ages less than 30 Myr) as well as a more extended population of intermediate-age (80–100 Myr) bright red stars. Knierman et al. (2003) used the *HST* WFPC2 to target a region midway along the southern tail, finding no significant population of bright ($M_V < -8$) star clusters.

NGC 4038/39 was targeted as part of the *Galaxy Evolution Explorer* (*GALEX*) Nearby Galaxies Survey (Bianchi et al. 2005a). When combined with existing ground-based optical colors, the UV colors provide an adequate color baseline to discriminate between stellar populations with ages ranging from 10 to 1000 Myr, spanning the dynamical age of the tails

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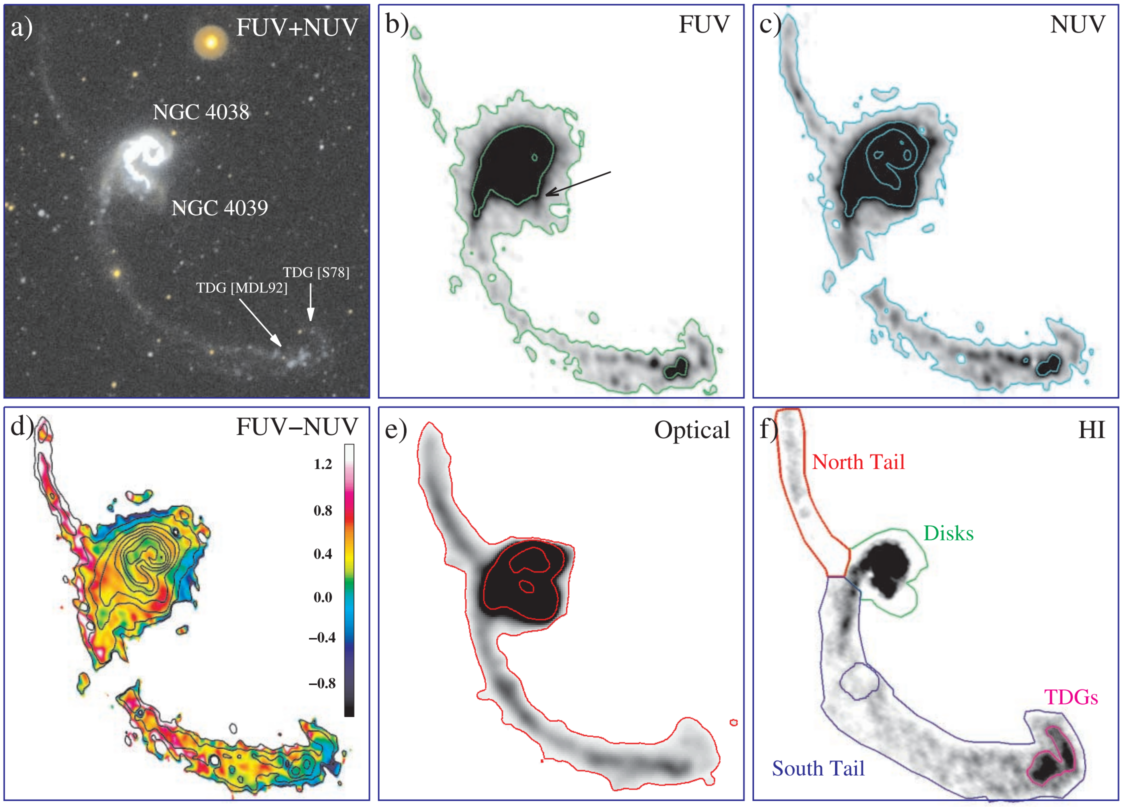

FIG. 1.—Montage of UV, optical, and H I observations of NGC 4038/39. (*a*) False-color representation of the full-resolution FUV and NUV data, where blue represents FUV emission, green a linear combination of FUV + NUV emission, and red NUV emission. The location of the TDG candidates identified by S78 and M92 is indicated. (*b*) Gray-scale image of the smoothed FUV emission. Contours are drawn at $\mu_{\rm FUV}$ = 29.5, 27.0, and 24.5 mag arcsec^{-2}. (*c*) Gray-scale image of smoothed NUV emission. Contours are drawn $\mu_{\rm NUV}$ = 29.5, 27.0, 24.5, and 22.0 mag arcsec^{-2}. (*d*) Color image of the FUV − NUV colors. Contours of the NUV surface brightness are drawn $\mu_{\rm FUV}$ = 29.5–21.5 mag arcsec^{-2} in steps of 1 mag arcsec^{-2}. (*e*) Smoothed star-subtracted *B*-band image convolved to 25″ resolution, from Hibbard et al. (2001). Contours are drawn at μ_B = 26.5, 24, and 21.5 mag arcsec^{-2}. The sharp northern and western edge of the optical disk in panel *e* is due to incomplete coverage of these regions by the optical CCD imaging. (*f*) Intermediate-resolution VLA H I data from Hibbard et al. (2001). Contours indicate the regions used to measure the global properties of the labeled regions reported in Table 1.

and allowing us to identify populations formed both before and after the tails were ejected. While the detailed *HST* observations mentioned above studied the youngest stellar populations at two small regions within the southern tail, the sensitivity and wide field of view of the new *GALEX* observations provides a complete census of ongoing and recent star formation along the entire tidal system, including the previously unstudied northern tail.

2. OBSERVATIONS AND RESULTS

The Antennae was observed by *GALEX* (Martin et al. 2005) on 2004 February 22 in four orbits with a total exposure time of 2554 s. The data reduction was done using the standard *GALEX* pipeline (Morrissey et al. 2005). The rms noise in the pipeline data is 27.83 AB mag arcsec^{-2} in the far-ultraviolet (FUV; 1550 Å) image and 28.02 AB mag arcsec^{-2} in the near-ultraviolet (NUV; 2310 Å) image. The FWHM of the FUV image is ∼5″, and that of the NUV image is ∼6″. We combine the *GALEX* observations with the optical and H I observations of Hibbard et al. (2001). For this comparison, the UV data were first edited to remove stars and then convolved to the resolution of the intermediate-resolution H I data (FWHM = 20″.7 × 15″.4). This means that we compare gas and UV properties averaged over spatial scales of 1.4 × 1.0 kpc^2. The resulting images reach limits of $\mu_{\rm UV} \sim 29.5$ mag arcsec^{-2}.

Figure 1 presents a montage comparing the FUV and NUV morphology to the optical and H I data of Hibbard et al. (2001). The full-resolution UV data are shown in Figure 1*a*, while the smoothed data are shown in Figures 1*b* and 1*c*. Figure 2 shows the full-resolution UV data of the inner disks and the end of the southern tail, with H I column density contours superposed. Table 1 lists global UV and optical magnitudes and colors of the different regions outlined in Figure 1*f*.

The smoothed UV emission is quite extended and structured, especially compared to the smoothed optical image (Fig. 1*e*). Remarkably, the H I map appears similarly structured (Fig. 1*f*). In fact, there is a close correspondence between H I column density peaks and UV emission. Most notable is the correspondence in the vicinity of the tidal dwarf candidates labeled in Figure 1*a* and the region immediate to the east of these regions (Fig. 2*b*). From the Very Large Array (VLA) H I channel maps, Hibbard et al. (2001) noted that the southern tail has a bifurcated structure, with two parallel gaseous filaments joining up at the location of the star-forming regions associated with TDG (M92). One filament coincides with the brighter optical spine of the tail, while another runs along the southern edge with little or no apparent optical counterpart ($\mu_B > 26$ mag arcsec^{-2}). The *GALEX* observations show a very similar bifurcated morphology that matches up well with the higher H I column density contours. NGC 4038/39 is yet another example of a seemingly general

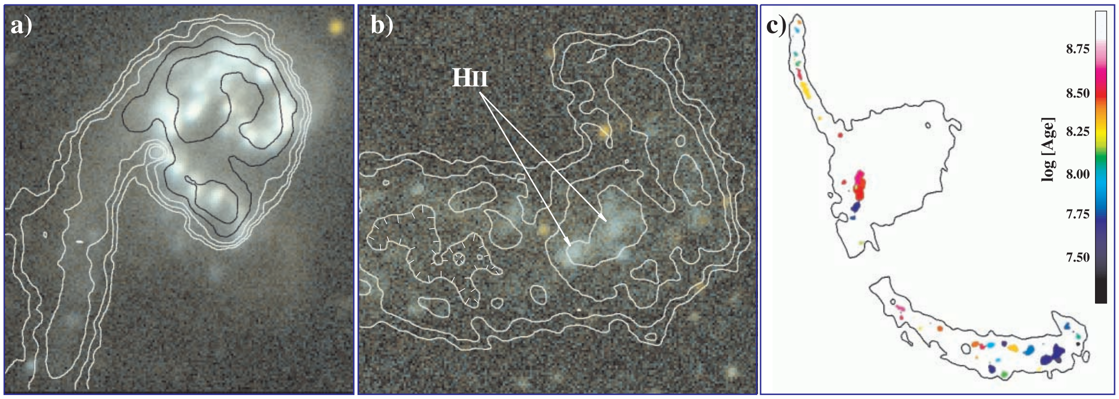

FIG. 2.—(*a*, *b*) Detail of inner disks (*left*) and TDG regions (*middle*). In this false-color image, blue represents FUV emission, green a linear combination of FUV + NUV emission, and red NUV emission. H I contours are drawn at (1, 2, 4, 8, 16) $M_\odot$ pc^{-2}. The location of the H II regions discovered by S78 are indicated in the middle panel. (*c*) SSP ages for selected UV-bright regions of the north and south tails, assuming only foreground extinction. The contour is drawn at $\mu_{\rm NUV} = 27.5$ mag arcsec^{-2}.

GALEX result that bright UV regions often correspond to H I column density peaks (e.g., Neff et al. 2005; Thilker et al. 2005; Xu et al. 2005).

Luminosity-weighted average ages for the stellar populations of the features delineated in Figure 1*f* were estimated by comparing the observed FUV − NUV and FUV − *V* colors with synthetic colors computed from reddened Bruzual & Charlot (2003) models, as described by Bianchi et al. (2005b). The foreground extinction value from the NASA/IPAC Extragalactic Database (NED), $E(B-V) = 0.046$, was adopted as a lower limit. In view of the associated H I gas, the intrinsic colors are likely bluer (especially for the disk and TDG regions), which would lower all the ages listed in Table 1.

The population ages were derived from models of single burst star formation (simple stellar population [SSP]). In the case of composite population, these ages give an indication of the age of the most recent burst, which dominates the UV fluxes. We also compared the observed colors with models of continuous star formation (composite stellar population [CSP]). Most regions are much redder than any CSP model, thus excluding this scenario. More extended model comparisons considering a variety of star formation scenarios are deferred to a subsequent paper.

Table 1 suggests a slightly older characteristic population for the north tail compared to the south tail. This difference is likely related to the very different gas contents of the two tails (Fig. 1*f*). The age estimates lie close to the expected dynamical age of the tail of ∼300 Myr (§ 1). So, in the absence of internal reddening, the global tail ages are consistent with little or no star formation subsequent to tidal ejection, with the exception of the TDG regions (known to harbor star-forming regions).

To get a better idea of whether star formation has proceeded in regions apart from the TDGs since the tails were ejected, we conducted photometry on other UV-bright complexes along the tails. The resulting color-coded ages are shown graphically in Figure 2*c*. Again we have assumed the minimum foreground reddening. In this figure, only regions with red or magenta colors have population ages as old or older than the dynamical age of the tails. Most of the UV-bright regions have populations that are significantly younger. This figure suggests that while the general stellar population of the tails is of the order of its dynamical age, there are a number of locations *besides the TDG regions* that have formed stars subsequent to the ejection of the tails. Figure 2*c* thus provides a valuable finding chart for future pointed observations in order to study extradisk star formation. We conclude that there has been some low-level in situ star formation within the tidal tails, mostly associated with the brighter UV regions and local gas density peaks.

Figure 2*c* further shows an indication of an age gradient, from ≈300 to less than 100 Myr, when moving outward along both tails. This gradient is hinted at by the FUV − NUV color map (Fig. 1*d*) and the $B-R$ color map of Hibbard et al. (2001), both of which become bluer with distance. For the two brightest clumps in the TDG region, somewhat discrepant ages are obtained from the FUV − NUV and FUV − *V* colors, suggesting a composite population. This is consistent with the results of Saviane et al. (2004), who find an extended population of intermediate-age (80–100 Myr) bright red stars in addition to

TABLE 1
GLOBAL PROPERTIES[a] FOR NGC 4038/39

Quantity	Disks	South Tail	North Tail	TDG[b]
$m_{\rm FUV}$	12.95 ± 0.001	16.38 ± 0.01	18.89 ± 0.07	17.71 ± 0.02
$m_{\rm NUV}$	12.62 ± 0.001	15.94 ± 0.02	17.66 ± 0.02	17.66 ± 0.01
m_V	10.39 ± 0.04	12.87 ± 0.04	13.93 ± 0.04	15.55 ± 0.04
FUV − NUV	0.33 ± 0.002	0.45 ± 0.02	1.24 ± 0.07	0.05 ± 0.02
FUV − *V*	2.56 ± 0.04	3.52 ± 0.04	4.96 ± 0.08	2.16 ± 0.04
Log (age)[c]	8.34 ± 0.08	8.49 ± 0.13	8.71 ± 0.10	8.08 ± 0.90

[a] Colors and magnitudes are on the AB system.
[b] Region encompassing TDG (S78) and TDG (M92); see Fig. 1*a*.
[c] Age for single burst model assuming only foreground Galactic reddening of $E(B-V) = 0.046$ (NED). The error includes both propagation of photometric errors and the difference in ages derived separately from the FUV − NUV and FUV − *V* colors, but not errors due to the uncertainty in the UV color zero point (see Morrissey et al. 2005).

the young stars and stellar associations in the TDG region (ages ≈4–30 Myr). The presence of similar mixed populations of young, intermediate-age, and older stars was inferred from *GALEX* measurements of tidal tails in other interacting galaxies (Neff et al. 2005).

Finally, the inner regions of the progenitor disks are shown in Figure 2*a*. While these regions will be the subject of a future paper, we note here several features brought out in the smoothed UV data. The first is that the FUV flux is sharply truncated in the southwestern part of the disk of NGC 4038 (see arrow in Fig. 1*b*). A similar sharp edge is seen in the H I disk (Fig. 2*a*). The UV color of this region is significantly redder than the rest of the disk ($\mathrm{FUV} - \mathrm{NUV} \sim 0.9$ mag, compared to 0.3 mag). Imaging of this region at a variety of wavelengths (e.g., Zhang et al. 2001) suggests that this is not due to dust, and the optical-NIR imaging of Kassin et al. (2003) suggests that the stellar population of this region is uniformly very old. This region is associated with the giant loops of hot thermal plasma ($kT \sim 0.3$ keV) imaged by *Chandra* (Fabbiano et al. 2004), raising the possibility that an X-ray wind swept this region clear of cold gas in the recent past, truncating star formation. On a larger scale, there is a halo of faint UV emission surrounding both disks (Figs. 1*b* and 1*c*). This emission is unlike that in the tails in that it is more extended in the FUV than the NUV (note the blue colors in Fig. 1*d*). It is uncertain whether there is a faint optical counterpart to this emission, since the optical CCD imaging did not extend this far. If there is no optical counterpart, then the emission may be associated with shocked gas in the recently discovered X-ray halo (Fabbiano et al. 2004).

3. CONCLUSIONS

We have studied the UV light within the archetypal merger NGC 4038/39, the Antennae. The tidal UV morphology is remarkably similar to the tidal H I, with a close correspondence between regions of bright UV emission and high H I column density. There are interesting features in the UV morphology of the inner regions. The FUV light in the southwestern half of the disk of NGC 4039 is sharply truncated, coincident with a similar truncation in the H I disk. This gas may have been removed by the X-ray loops recently imaged in this system by *Chandra* (Fabbiano et al. 2004), inhibiting subsequent star formation. On a larger scale, there is a FUV "halo," possibly related to shocked gas in the X-ray halo.

While it has long been known that tails are generally blue (§ 1), the *GALEX* observation provides color baselines to determine how much of the UV radiation comes from stars younger than the dynamical age of the tails. A preliminary analysis suggests that most of the stars within the tidal tails date to before the tail formation period. The population in the northern tail appears older than that in the southern tail. Examining individual UV-bright regions within the tails, we find regions of more recent star formation, which occur at regions of higher H I column density and extend well beyond the previously identified tail star-forming regions. The tails are thus a promising laboratory for studying extradisk star formation and testing theories of star and cluster formation.

The present results are for a very simplistic star formation history. A future analysis will include more complicated star formation histories and will incorporate all available UV-to-optical colors of the tails. The UV color baselines should enable us not only to identify current star-forming regions but to examine and date regions of past star formation. By comparing the number of regions of a given age and the star formation history in individual knots, we will be able to test whether long-lived condensations form within tidal tails.

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