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

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ABSTRACT

We present GALEX FUV (1530 Å) and NUV (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 putative Tidal Dwarf Galaxy 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, and not just at the previously studied Tidal Dwarf region. Within the inner disk regions, there are interesting UV features which appear to be related to the recently discovered extended X-ray plasmas.

Subject headings: galaxies: interactions – galaxies: intergalactic medium – galaxies: ISM – galaxies: starburst – galaxies: individual (NGC 4038/39) – ultraviolet: galaxies

1. INTRODUCTION

It has long been know that tidal filaments have blue optical colors, with regions as blue or bluer than the spiral arms of disk galaxies (Zwicky 1956, Vorontsov-Vel'yaminov 1962, Arp 1966, Schweizer 1978, Schombert, Wallin, & Struck-Marcell 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 spirals several 10^8 yrs ago, or if they reflect on-going and pervasive tidal star-formation.

Localized regions of current tidal star formation have been unambiguously identified via the optical emission lines of young (<10 Myr) stars (e.g. Stockton 1974a,b, Schweizer 1978, Hibbard & van Gorkom 1996, Iglesias-Páramo & Vílchez 2001, Weilbacher, Duc, & Fritze-v.Alvensleben 2003). And recently individual young stars (Saviane, Hibbard & Rich 2004) and star clusters (Kniermann 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 TRGB distance of 13.8 Mpc (Saviane et al. 2004; used throughout), the Antennae is the nearest on-going 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, Fall & Whitmore 2001, Kassin et al. 2003), and these regions are indeed prolific emitters of UV radiation. 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 either from 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).

Schweizer (1978) discovered several H II regions near the end of the southern tail of NGC 4038, and identified a low surface brightness region further along as a possible "Tidal Dwarf Galaxy" (TDG): a dwarf galaxy-sized self-gravitating object formed within the tidal debris (e.g. Duc & Mirabel 1999). We refer to this region in the following as TDG[S78]. Mirabel et al. (1992) further studied the tidal H II regions identified by Schweizer, and suggested that this too was a separate forming Tidal Dwarf (hereafter TDG[MDL92]). The H I gas in these regions were studied by Hibbard et al. (2001), who found no kinematic evidence for a massive ($M_{dyn} \sim 10^9 M_{\odot}$) self-gravitating object, and suggested that there were instead several smaller condensations within the tail associated with the star forming regions. The stellar population of the TDG[MDL92] region was studied by Saviane et al. (2004), who found a population of eight young stellar associations (ages less than 30 Myr), as well as more extended population of intermediate aged (80–100 Myr) bright red stars. However, the imaged field did not

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TABLE 1
Global Properties[a] for NGC 4038/39

Quantity	Disks	South Tail	North Tail	TDG [b]
m_{FUV}	12.95±0.001	16.38±0.01	18.89±0.07	17.71±0.02
m_{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
$F-N$	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] UV colors are on the AB system while optical colors are on the Vega system. The errors in the optical colors are dominated by uncertainty in the color zero-point.
[b] Region encompassing Tidal Dwarf Candidates TDG[S78] and TDG[MDL92]; see Fig.1a.
[c] Age for single burst model assuming only foreground Galactic reddening of $E(B-V)$=0.048 (NED). The error includes both propagation of photometric errors and the difference in ages derived separately from the $FUV-NUV$ and $FUV-V$ colors.

extend much beyond the TDG[MDL92] region. Kniermann et al. (2003) targeted a region midway along the southern tail, finding no significant population of bright ($M_V < -8$) star clusters.

2. OBSERVATIONS

The Antennae was observed by GALEX (Martin et al. 2004) on 2004-02-22 in four orbits with the total exposure time of 2554 seconds. The data reduction was done using the standard GALEX pipeline (Morrissey et al. 2004). The r.m.s noise in the pipeline data is 27.83 AB mag arcsec^{-2} in the FUV (1550Å) image and 28.02 AB mag arcsec^{-2} in the NUV (2310Å) image. The FWHM of the FUV beam is $\sim 5''$, and that of the NUV beam is $\sim 6''$.

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 (as identified from optical imaging) and then convolved to the resolution of the intermediate resolution H I data (FWHM=$20.7'' \times 15.4''$). This means we will be comparing gas and UV properties averaged over spatial scales of 1.4×1.0 kpc^2. The resulting images reach limits of μ_{UV} ~29.5 mag arcsec^{-2}.

3. RESULTS

Figure 1 presents a montage comparing the FUV and NUV morphology to the optical and H I data of Hibbard et al. (2001). The sharp northern and western edge of the optical disk in Fig. 1e is due to incomplete coverage of these regions by the optical CCD imaging. Figure 2 shows a close-up of the inner disks and the end of the southern tail, with H I column density contours superimposed. Table 1 lists global UV and optical magnitudes and colors of the different regions outlined in Fig. 1f.

The smoothed UV emission is quite extended and structured, especially compared to the smoothed optical image (Fig. 1e). Remarkably, the H I map appears similarly structured (Fig. 1f). In fact, there is a close correspondence between H I column density peaks and UV emission. Most notable is the bright UV emission from the vicinity of the tidal dwarf candidates labeled in Fig. 1a, and the region immediate to the east of these regions (Fig. 2b). From the VLA H I channel maps, Hibbard et al. (2001) noticed 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[MDL92]. 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 which matches up well with the higher H I column density contours.

The close match between the UV and H I morphology was investigated by plotting FUV surface brightness against H I column density. We find that wherever the H I column density is high, the associated UV flux density is also high. More interestingly, there is no obvious "critical" H I surface density below which the UV surface brightness drops abruptly. However, it is difficult to draw stronger conclusions. The UV data should be corrected for internal extinction, and the H I data should be supplemented with other gas tracers, especially CO. We defer such a treatment to a future paper.

Average ages for the stellar populations of the features delineated in Fig. 1f were estimated by comparing the observed $FUV-NUV$ and $FUV-V$ colors with synthetic colors computed from Bruzual & Charlot (2003) models, as described by Bianchi et al. (2004). The foreground extinction value from the NED database, E(B-V)=0.046, was adopted as a lower limit. The true colors are likely bluer (especially for the disk and TDG regions), which would lower all the ages given in Table 1.

The population ages were derived from models of Single Burst star formation (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 (CSP). Most regions are redder than any CSP model, thus excluding this scenario. A plausible SF scenario for these regions may be an intermediate case between SSP and CSP. More extended model comparisons 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. 1f). 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 (which were known to be forming stars).

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 Fig. 2c. 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 which are significantly younger. This figure suggests that, while the general stellar population of the tails is of order its dynamical age, there are a number of locations *besides the TDG regions* which have formed stars subsequent to the ejection of the tails. We conclude that there has been some low-level *in situ* star for-

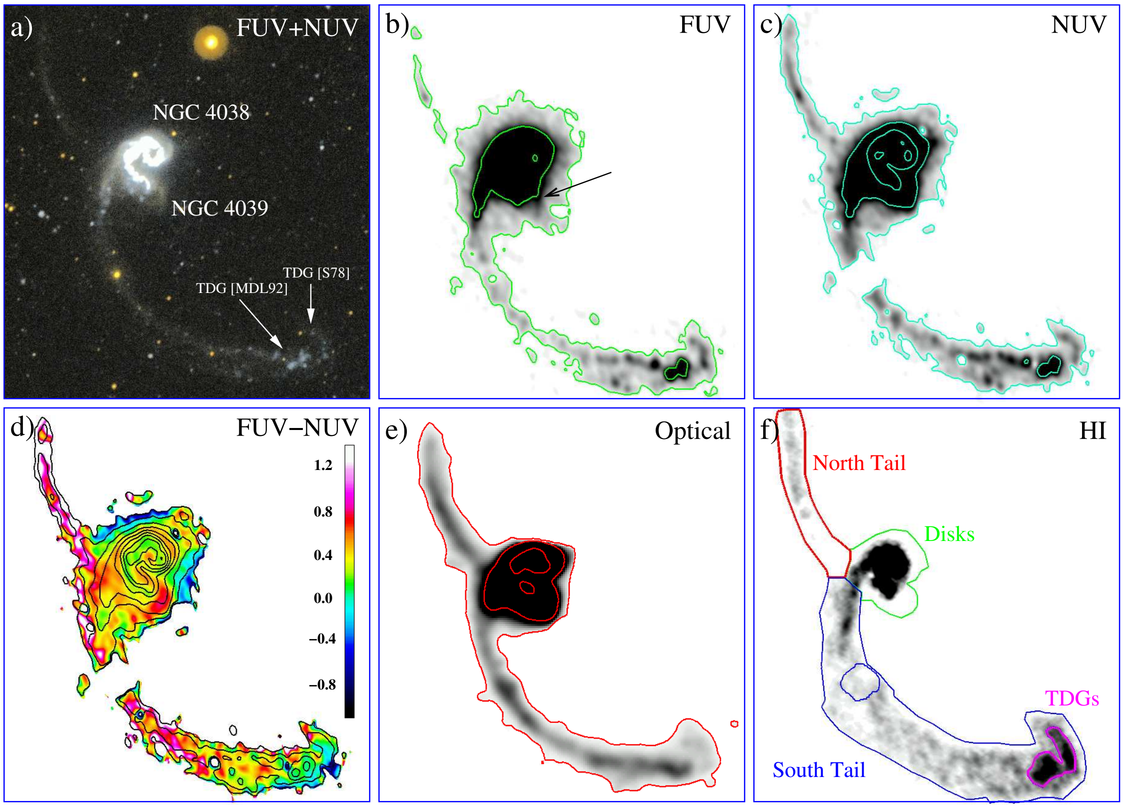

FIG. 1.— Montage of UV, optical and H I observations of NGC 4038/39. **(a)** A false-color representation of the full resolution FUV and NUV data, where blue represents FUV emission, green a linear combination of $FUV + NUV$ emission, and red the NUV emission. **(b)** Greyscale image of the smoothed FUV emission. Contours are drawn at μ_{FUV}=29.5, 27.0, 24.5 mag arcsec^{-2}. **(c)** Greyscale image of smoothed NUV emission. Contours are drawn μ_{NUV}29.5, 27.0, 24.5, 22.0 mag arcsec^{-2}. **(d)** A color image of the $FUV - NUV$ colors. Contours of the NUV surface brightness are drawn μ_{FUV}=29.5 to 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, 21.5 mag arcsec^{-2}. **(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.

mation within the tidal tails, mostly associated with the brighter UV regions and local gas density peaks. This is another example of a seemingly general GALEX result that bright UV regions often correspond to H I column density peaks (e.g., Neff et al. 2004, Thilker et al. 2004, Xu et al. 2004).

Fig. 2c further shows an indication of an age gradient, from $\approx$ 300 Myrs to less than 100 Myrs, when moving outward along both tails. This gradient is hinted at by the $FUV - NUV$ color map (Fig. 1d) 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 found an extended population of intermediate aged (80–100 Myr) bright red stars in addition to the young stars and stellar associations in the TDG region (ages $\approx 4 - 30$ Myr). The presence of similar mixed populations of young, intermediate aged, and older stars was inferred from GALEX measurements of tidal tails in other interacting galaxies (Neff et al. 2004).

Finally, the inner regions of the progenitor disks are shown in Fig. 2a. While these regions will be the subject of a future paper, we note here that the FUV flux is sharply truncated in the southwestern part of the disk of NGC 4038 (see arrow in Fig. 1b), immediately after a similar truncation in the H I disk (Fig. 2a). The UV color of this region is significantly redder than the rest of the disk ($FUV - NUV$ ~0.9 mag, compared to 0.3 mag). Imaging of this region at a variety of wavelengths (e.g. Zhang, Fall & Whitmore 2001) suggest that this is not due to dust, and the optical-NIR imaging of Kassin et al. (2003) suggest that the stellar population of this region is uniformly very old. This region is associated with the giant loops of hot thermal plasma (kT ~ 0.3 keV) imaged by Chandra (Fabbiano et al. 2004). On a larger scale, there is a halo of faint UV emission surrounding both disks (Fig. 1b,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. 1d). Its uncertain whether there is 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 X-ray halo.

4. CONCLUSIONS

We haved studied the UV light within the archetypal merger NGC 4038/39. The tidal UV morphology is remarkably similar morphology to the tidal H I, with a close correspondance between regions of bright UV emission and high H I column density. There are interesting

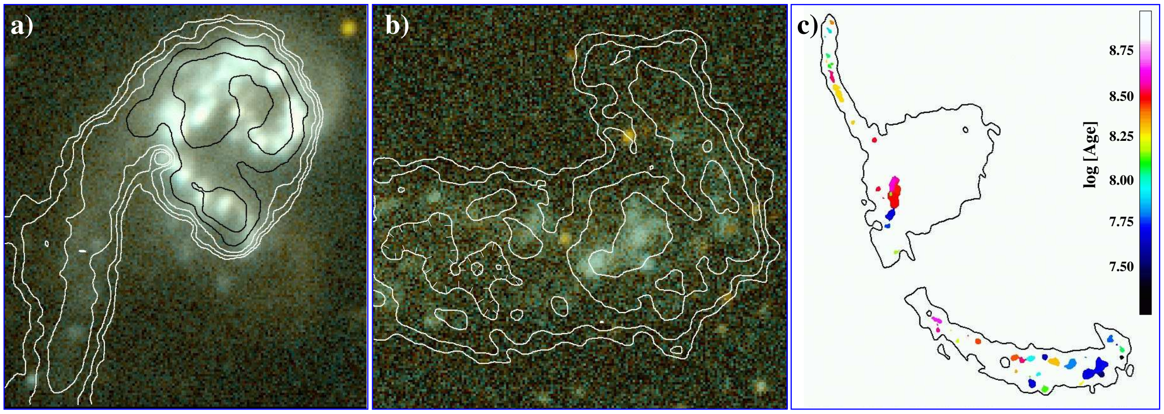

FIG. 2.— Left and Middle: Close-up of inner disks (left) and TDG regions (middle), with H I column density contours superimposed. The false-color is the same representation as in Fig. 1a. H I contours are drawn starting at a column density of 1 $M_{\odot}\mathrm{pc}^{-2}$ ($1.26 \times 10^{20}\,\mathrm{cm}^{-2}$), with subsequent contours a factor of two higher. Right: SSP Ages for selected UV bright regions of the north and south tails, assuming only foreground extinction. The contour is drawn at $\mu_{NUV} = 27.5$ mag arcsec^{-2}.

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 bubbles recently imaged in this system by `Chandra` (Fabbiano et al. 2004). 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 provide 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 redder 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 than average H I column density, and extend well beyond the previously identified TDG star forming regions. The tails are thus a promising laboratory for studying extra-disk 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 to not only 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 condensation form within tidal tails.

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