ULTRAVIOLET EMISSION AND STAR FORMATION IN STEPHAN’S QUINTET

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ABSTRACT

We present the first Galaxy Evolution Explorer (GALEX) UV images of the well-known interacting group of galaxies, Stephan’s Quintet (SQ). We detect widespread UV emission throughout the group. However, there is no consistent coincidence between UV structure and emission in the optical, Hα, or Hβ. Excluding the foreground galaxy NGC 7320 (Sd), most of the UV emission is found in regions associated with the two spiral members of the group, NGC 7319 and NGC 7318b, and the intragroup medium starburst SQ-A. The extinction-corrected UV data are analyzed to investigate the overall star formation activity in SQ. We find that the total star formation rate (SFR) of SQ is 6.69 ± 0.65 M⊙ yr⁻¹. Of this, 1.34 ± 0.16 M⊙ yr⁻¹ is due to SQ-A. This is in excellent agreement with that derived from the extinction-corrected Hα luminosity of SQ-A. The SFR in regions related to NGC 7319 is 1.98 ± 0.58 M⊙ yr⁻¹, most of which (68%) is contributed by the disk. The contribution from the “young tail” is only 15%. In the UV, the young tail is more extended (∼100 kpc) and shows a looplike structure, including the optical tail, the extragalactic H ii regions recently discovered in Hα, and other UV emission regions discovered for the first time. The UV and optical colors of the “old tail” are consistent with a single stellar population of age t = 10⁸±5·10⁹ yr. The UV emission associated with NGC 7318b is found in a very large (∼80 kpc) disk, with a net SFR of 3.37 ± 0.25 M⊙ yr⁻¹. Several large UV emission regions are 30–40 kpc away from the nucleus of NGC 7318b. Although both NGC 7319 and NGC 7318b show peculiar UV morphology, their SFR is consistent with that of normal Sbc galaxies, indicating that the strength of star formation activity is not enhanced by interactions.

Subject headings: galaxies: active — galaxies: interactions — galaxies: ISM — galaxies: starburst — intergalactic medium — stars: formation

Online material: machine-readable table

1. INTRODUCTION

Stephan’s Quintet (hereafter SQ) includes NGC 7317 (E), binary galaxies NGC 7318a (E) and NGC 7318b (Sbc pec), Seyfert 2 galaxy NGC 7319 (Sbc pec), and the foreground galaxy NGC 7320 (Sd). Two very long parallel optical tidal tails (>100 kpc; Arp & Kormendy 1972) extend from the south end of NGC 7319 toward another galaxy, NGC 7320c, east of SQ. The H i observations (Shostak et al. 1984; Williams et al. 2002, hereafter W02) show H i tails following the optical tails. A large-scale shock front (∼40 kpc) in the intragroup medium (IGM) between NGC 7319 and NGC 7318b was first discovered by Allen & Hartsuiker (1972) as a radio emission ridge, then confirmed by high-resolution X-ray maps (Trinchieri et al. 2003). Moles et al. (1997, hereafter M97) suggested a “two-intruders” scenario for the history of SQ: an old intruder (NGC 7320c) stripped most of the gas from group members, and a new intruder (NGC 7318b) is currently colliding with this gas and triggered the large-scale shock. There are still many uncertainties about this scenario. These include the question of whether both optical tails, one of age ∼10⁸ yr (“young tail”) and another of age ∼5 × 10⁷–10⁸ yr (“old tail”), are triggered by two passages of the same galaxy, NGC 7320c, over NGC 7319 (M97). In addition, new H i maps show that the H i in the region occupied by NGC 7318b is clearly separated into two clumps with distinctively different velocities. Based on this, W02 challenged the conclusion that NGC 7318b was not affected by interaction until its collision with SQ, starting about 10⁸ yr ago (Sulentic et al. 2001, hereafter S01).

The star formation activity in SQ is apparently very much influenced by the interactions. The most spectacular star formation region in SQ is the IGM starburst SQ-A, which is associated with a bright mid-infrared (MIR; 15 μm) source (Xu et al. 1999, hereafter X99) just beyond the northern tip of the shock front. It is triggered by the same NGC 7318b/IGM collision that triggered the shock (Xu et al. 2003, hereafter X03). The young tail, the brighter one among the two optical tails, is also active in star formation. Hunsberger et al. (1996) found 13 “tidal dwarf galaxy candidates” along this tail. A bright H ii region (SQ-B) is detect in both Hα (Arp 1973) and MIR (X99).
Recently, Mendes de Oliveira et al. (2004, hereafter MdO04) discovered several intergalactic H\textsc{ii} regions in a region north of the young tail (see also S01), possibly associated with the stripped interstellar medium of NGC 7319 (S01). The H\textalpha observations (Arp 1973; Vílchez & Iglesias-Páramo 1998; Planas et al. 1999; S01) reveal numerous H\textsc{ii} regions along several arms of NGC 7318b. Hunsberger et al. (1996), Iglesias-Páramo & Vílchez (2001), and Mendes de Oliveira et al. (2001) classified them as tidal dwarf galaxy candidates, although S01 argued that the crossing time of NGC 7318b (∼10$^7$ yr) is too short for any tidal effects. There has been no estimate of the total star formation rate (SFR) in SQ in the literature. Therefore, it is not clear whether the overall star formation activity is enhanced by the interactions. In addition, because a clear picture for the interaction history of SQ is still missing, most results in the literature linking the star formation activity to interactions in SQ were at best suggestive.

In this Letter we present the first UV images of SQ obtained using the Galaxy Evolution Explorer (GALEX; Martin et al. 2005). The GALEX observations are sensitive to very low levels of star formation averaged over ∼10$^6$ yr, the timescale of the tidal effects. This enables the first quantitative study of the overall star formation and its distribution in SQ. Comparisons between the UV, optical, H\textalpha, and the emission in other wavebands put new constraints on the star formation history and on the relation between star formation and galaxy-galaxy interaction.

### 2. GALEX OBSERVATIONS

SQ was observed by GALEX on 2003 August 23, 2003 September 5, and 2003 September 6 in five orbits, with total exposure time of 3327 s. Data reduction was done using standard GALEX pipeline (IR0.2 calibration; Morrissey et al. 2005). The rms noise is 27.65 mag arcsec$^{-2}$ and 28.11 mag arcsec$^{-2}$ in the far-UV (FUV; 1530 Å) and near-UV (NUV; 2310 Å), respectively. The UV magnitudes are in the AB system. The FWHM of the FUV beam is 47′, for NUV beam it is 73′.

The GALEX image (Fig. 1a) looks very different from the optical image (Fig. 1b). The foreground Sd galaxy NGC 7320 is the most prominent UV source, but as NGC 7320 is not a member of SQ, we do not discuss it further. A striking feature of the UV emission in SQ is that there are large regions that do not coincide with significant optical light from the galaxies or optically detected tidal features. This is in contrast to the merger that gives rise to the Antennae (Hibbard et al. 2005), where the UV emission is seen to follow the tidal tails and merger body closely.

There is an extended UV disk (outlined by the red ellipse in the UV image) centered between the nuclei of NGC 7318a and NGC 7318b. It is most likely to be associated with NGC 7318b, and the contribution from NGC 7318a is insignificant. This is because NGC 7318a has the optical appearance of an ordinary elliptical galaxy, and no H\textsc{ii} regions or H\textalpha gas in this area is likely to be associated with it (M97; S01). The UV disk, with a physical size of ∼80 kpc, is about 1′ larger (along the major axis) than the disk found by S01 on the $B-R$ image. The emission peaks in the south side of the UV disk are in good agreement with those in the H\textalpha gas in this region, which has the same redshift as NGC 7318b (W02). This agrees with the results of Thilker et al. (2005), who found that the UV emission regions in the outer disk of M83 are typically associated with H\textsc{ii} structures. The north tip of the disk goes beyond the H\textalpha gas boundary (Fig. 1c). This discrepancy between the UV and the cold gas may well be due to the shock. SQ-A is also located within this disk.

The Seyfert 2 nucleus of NGC 7319 is faint in the UV, indicating very high extinction within the active galactic nucleus (AGN), consistent with the Seyfert 2 classification. Both the young and old tails are detected. The young tail looks more like a loop in the UV image. Compared to the optical tail, it extends farther in the northeast direction and includes the four intergalactic H\textsc{ii} regions found by MdO04. The UV emission within the NGC 7319 disk shows a disturbed morphology. It is interesting to note that no H\textalpha gas has been detected in the NGC 7319 disk (Fig. 1c; W02). The UV emission in the northeast part of the disk is along two strong optical arms. It does not coincide with the H\textalpha emission, nor with the CO emission (Fig. 1c). The elliptical galaxy NGC 7317 is faint in the UV, and there is no indication that it has been involved in any recent interactions with other members of SQ.

### 3. STAR FORMATION IN SQ

The UV data are analyzed quantitatively to study the star formation activity in different regions in SQ. The results are presented in Table 1. For both the FUV and NUV magnitudes, a calibration uncertainty of 0.1 mag is assumed (Morrissey et al. 2005). The FUV magnitude and the FUV − NUV
**TABLE 1**

Star Formation Properties in SQ Regions

| Name                  | Region | FUV (mag) | log $L_{FUV}$ ($L_\odot$) | SFR ($M_\odot$ yr$^{-1}$) | FUV − NUV (mag) | log $t_{FUV}$ (yr) | $B − V$ (mag) | log $I_{FUV}$ (yr) | $A_{FUV}$ (mag) |
|-----------------------|--------|-----------|---------------------------|----------------------------|-----------------|-----------------|----------------|-----------------|----------------|
| Old tail              | I      | 19.74 ± 0.12 | 8.49 ± 0.08 | 0.060 ± 0.013 | 0.44 ± 0.16 | 8.4 ± 0.2 | 0.28 ± 0.15 | 8.5 ± 0.4 | 0.17 ± 0.17 |
| Young tail            | II     | 18.14 ± 0.11 | 9.18 ± 0.07 | 0.296 ± 0.051 | 0.21 ± 0.15 | 7.9 ± 0.3 | 0.45 ± 0.14 | 8.7 ± 0.3 | 0.31 ± 0.14 |
| Tail/disk overlap     | III    | 19.34 ± 0.12 | 9.17 ± 0.06 | 0.285 ± 0.046 | 0.43 ± 0.16 | 7.9 ± 0.3 | 0.69 ± 0.14 | 8.9 ± 0.3 | 1.47 ± 0.11 |
| NGC 7319 disk$^a$     | IV     | 18.19 ± 0.11 | 9.84 ± 0.15 | 1.341 ± 0.571 | 0.77 ± 0.15 | 8.3 ± 0.3 | 0.77 ± 0.14 | 9.0 ± 0.3 | 2.00 ± 0.37 |
| Shock front           | V      | 16.87 ± 0.10 | 9.87 ± 0.05 | 1.450 ± 0.164 | 0.31 ± 0.14 | 7.9 ± 0.3 | 0.55 ± 0.14 | 8.8 ± 0.2 | 0.76 ± 0.06 |
| SQ-A                  | VI     | 17.32 ± 0.10 | 9.86 ± 0.05 | 1.335 ± 0.156 | 0.27 ± 0.14 | 7.4 ± 0.6 | 0.44 ± 0.14 | 8.7 ± 0.3 | 1.12 ± 0.07 |
| NGC 7318b inner disk  | VII    | 16.76 ± 0.10 | 9.91 ± 0.05 | 1.561 ± 0.179 | 0.39 ± 0.14 | 8.1 ± 0.3 | 0.86 ± 0.14 | 9.3 ± 0.3 | 0.74 ± 0.06 |
| NGC 7318b outer disk  | VIII   | 17.72 ± 0.11 | 9.33 ± 0.06 | 0.360 ± 0.052 | 0.02 ± 0.15 | 7.4 ± 0.5 | 0.38 ± 0.14 | 8.7 ± 0.2 | 0.10 ± 0.10 |
| Total                 |        | 15.36 ± 0.10 | 10.54 ± 0.05 | 6.687 ± 0.646 | 0.33 ± 0.14 | ...     | ...          | ...          | ...          |

Note.—Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content. Col. (3): FUV corrected for the foreground Galactic extinction. Col. (4): Extinction-corrected FUV luminosity (corrected for both Galactic and internal extinction). The error includes the uncertainty of the extinction correction. Col. (6): UV color corrected only for the Galactic extinction. Col. (7): Stellar population age derived from extinction-corrected UV color, using the single-population model. The error includes the uncertainty of the extinction correction. Col. (8): Optical color corrected only for the Galactic extinction. Col. (9): Stellar population age derived from extinction-corrected optical color, using the single-population model.

$^a$ Contribution from the AGN is subtracted from the UV, optical, and MIR flux densities.

$B − V$ colors in Table 1 are corrected for foreground Galactic extinction $E(B − V) = 0.079$ and the extinction curve of Cardelli et al. (1989). For regions detected in the ISOCAM 15 μm map (X99), the internal extinction is determined using the luminosity ratio $\log (L_{15\mu m}/L_{FUV})$, according to the formula

$$Y = \log (L_{IR}/L_{FUV}) = \log (L_{15\mu m}/L_{FUV}) + 1.04,$$

$$A_{FUV} = -0.033Y^1 + 0.352Y^2 + 1.196Y + 0.497.$$  

The relation $\log L_{IR} = \log (L_{15\mu m} + 1.04$ is taken from Chary & Elbaz (2001). Equation (2) is taken from Buat et al. (2005). Other regions are either undetected or outside the ISOCAM 15 μm map. For those, the internal extinction is estimated using the average H I column density (W02) and the dust-to-gas ratio of the solar neighborhood ($\tau_g = 5.8 \times 10^{-22}$ atom$^{-3}$ cm$^{-2}$; Savage & Mathis 1979). The foreground screen model and a modified Calzetti attenuation curve (Buat et al. 2005) are assumed. For the extinction estimated using the H I, the error is assumed to be 100%. Estimates of the internal extinction of region VI (SQ-A) using the MIR-to-FUV ratio and the H I column density, respectively, are found to be consistent with each other. The star formation rate is estimated using the extinction-corrected FUV luminosity, according to the formula of Kennicutt (1998). The age of the stellar population responsible for the UV emission is determined using the extinction-corrected FUV − NUV color and the single population synthesis model (i.e., the burst model) of Fioe & Rocca-Volmerange (1997; PEGASE). This is compared with the age of the stellar population responsible for the optical emission, determined using the extinction-corrected $B − V$ color and the same synthesis model.

SFR of SQ-A (region VI).—The SFR of $1.34 \pm 0.16 M_\odot$ yr$^{-1}$ estimated from the extinction-corrected FUV luminosity is in excellent agreement with that from the extinction-corrected Hα luminosity ($1.45 M_\odot$ yr$^{-1}$) from X03. On the other hand, the extinction estimated from the MIR-to-FUV ratio ($A_{FUV} = 0.76 \pm 0.06$) is lower than that indicated by the Balmer decrement ($A_{H\alpha} \sim 0.6–2$). This suggests that O and B stars, which are responsible for the ionizing and nonionizing UV radiation, respectively, have different distributions relative to the dust. The UV and optical colors indicate two separate stellar populations, one of age $10^{7.4士0.6}$ yr and another of $10^{8.7士0.3}$ yr. This is consistent with the results of Gallagher et al. (2001).

Star formation in regions related to NGC 7319.—These include regions I, II, III, and IV. Among the net SFR of $1.98 \pm 0.58 M_\odot$ yr$^{-1}$, 68% is contributed by the disk (region IV), and 15% from the young tail (region II). There is a disk/tidal-tail gradient among the underreddened UV colors of regions IV, III, and II (Fig. 2b). However, the extinction-corrected UV colors are consistent with each other (Fig. 2c), indicating that the color gradient is mainly due to the dust reddening, and there is no significant difference in the age of the UV population in the disk and in the tail. The extinction-corrected UV and optical colors of region I (old tail) are consistent with a single population of age $t = 10^{8.5士0.4}$ yr, somewhat younger than that estimated by S01 from dynamic arguments ([$6–12] \times 10^{7}$ yr).

Region II includes 11 subregions (see Fig. 2a and the electronic version of Table 1). IIa, IIb, and IIc correspond to the optical tail. The age of the UV population in IIa and IIb is $\sim 10^{7}$ yr, while that of the optical population is $\sim 5 \times 10^{6}$ yr, indicating an old underlying population possibly stripped from the disk of NGC 7319 in the encounter. The bright Hα/MIR source SQ-B is in the east end of IIa, signaling active current star formation. IIc has a much younger UV population ($\sim 10^{8}$ yr). It is outside our $B$ and $V$ images. The extragalactic H II regions found by MdO04 are also in region II. Subregion IIi (c and d in MdO04) shows very young ages in both UV and optical colors ($\sim 10^{6}$ yr), consistent with the Hα equivalent line width (E(W[Hα])) result of MdO04. Subregion IIj, which is north of IIi and is not in the list of MdO04, shows properties similar to IIi. The UV population of IIe (b in MdO04) has an age of $log t = 7.7 \pm 0.7$, older than that estimated by MdO04 (5.6 Myr) from the E(W[Hα]). In the UV image, these subregions, together with other subregions that are discovered for the first time, form a looplike structure. Given that many of these subregions were also detected in other bands (e.g., optical and Hα), and that available redshift data (S01; MdO04) are consistent with their having the same redshift, this structure is very likely real. M97 suggested that the young tail is triggered by a high-velocity (700 km s$^{-1}$) passage of NGC 7320c through NGC 7319 $1.5 \times 10^{8}$ yr ago. However, the recently measured redshift of NGC 7320c is almost identical to that of NGC 7319, indicating instead a slow passage (S01). Therefore, in order for NGC 7320c to move to its current position, the NGC 7319/NGC 7320c encounter must have occurred $\geq 5 \times 10^{8}$ yr ago. This is close to the age of the old tail, but older than that of the young tail (M97). An alternative scenario is that the young tail is triggered by a close encounter between...
NGC 7319 and the elliptical galaxy NGC 7318a. Since NGC 7318a is about 3 times closer to NGC 7319 than NGC 7320c, the time argument is in favor of this new scenario. In addition, the “UV loop” on the other side of NGC 7319 with regard to NGC 7318a looks very similar to the counter tidal tail found frequently in the dynamic simulations of galaxy-galaxy interactions (see, e.g., Fig. 2 of Toomre & Toomre 1972; \( t = 2 \times 10^8 \) yr), lending further support to the new scenario.

**Star formation in regions related to NGC 7318b.**—These include regions V, VII, and VIII. The peaks of the UV emission in region V correspond to a chain of \( \text{HI} \) regions in one of star-forming arms of NGC 7318b (S01; Gallagher et al. 2001). Therefore, most of the UV emission is likely associated with the star formation, rather than with the shock. The total SFR is \( 3.37 \pm 0.25 \, M_\odot \, \text{yr}^{-1} \), which is about \( 10^7 \, M_\odot \) yr\(^{-1}\); Mezger 1988), a normal Sbc galaxy. Region VIII includes four subregions; VIIIa and VIIIb are in the south end of the UV disk, and VIIIc and VIIIId in the north end. They are \( 30-40 \, \text{kpc} \) away from the nucleus of NGC 7318b. These are even larger than the largest distance among the UV emission regions in the extreme outer disk of M83, studied by Thilker et al. (2005). Whether the remarkable size of this UV disk, the peculiar morphology of the \( \text{HI} \) gas, and the long and open arms (tidal tails!!) of NGC 7318b are due to a head-on collision with NGC 7318a about \( 10^8 \) yr ago (X03) is an interesting subject for future studies. The UV and optical colors of VIIIa are consistent with a single population of \( \sim 10^8 \) yr.

**Summary remarks.**—Every time SQ is observed in a waveband for the first time, it reveals new, spectacular phenomena related to its complex interaction history. The long-term fate of the star-forming regions in the IGM starburst SQ-A, in the remarkably extended “UV loop” associated with the “young tail,” and in the very large UV disk of NGC 7318b is of great interest. This can have far-reaching implications for interaction-induced star formation in multigalaxy systems, which may play important roles in the early universe.

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