UV emission and Star Formation in Stephan's Quintet

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ABSTRACT

We present the first *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, $H\alpha$, or HI. 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. It is found that the total star formation rate (SFR) of SQ is 6.69±0.65 $M_\odot$ yr^{-1}. Among this, 1.34±0.16 $M_\odot$ yr^{-1} is due to SQ-A. This is in excellent agreement with that derived from extinction corrected

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Hα luminosity of SQ-A. The SFR in regions related to NGC 7319 is 1.98±0.58 $M_\odot$ 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 ($\sim$ 100 kpc) and shows a loop-like structure, including the optical tail, the extragalactic HII 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 $t \simeq 10^{8.5\pm0.4}$ yrs. The UV emission associated with NGC 7318b is found in a very large ($\sim$ 80 kpc) disk, with a net SFR of 3.37±0.25 $M_\odot$ 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 enhenced by interactions.

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

1. Introduction

Stephan's Quintet (hereafter SQ) includes NGC 7317 (E), binary galaxies NGC 7318a (E) and NGC 7318b (Sbc pec), Sy2 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 on the east of SQ. The HI observations (Shostak et al. 1984; Williams et al. 2002, hereafter W02) show HI tails following the optical tails. A large scale shock front ($\sim$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 whether both optical tails, one of age $\sim 10^8$ yrs ('young tail') and another of age $\sim 5\ 10^8$ — 10^9 yrs ('old tail'), are triggered by two passages of the same galaxy NGC 7320c over NGC 7319 (M97). Also, based on new HI maps which show that the HI in the region occupied by NGC 7318b is clearly separated into two clumps with distinctively different velocities, W02 challenged the conclusion that NGC 7318b was *not* affected by interaction until its collision with SQ starting about 10^7 yrs ago (S01).

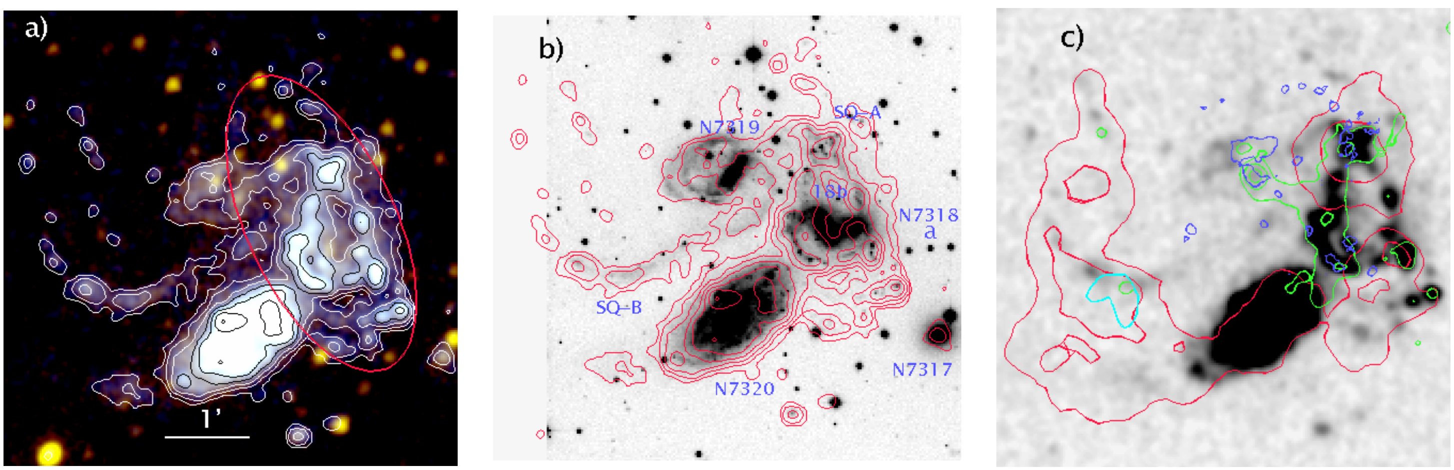

Fig. 1.— **(a)** Composite UV color image of SQ (blue: FUV, green: FUV+NUV, red: NUV). In order to match the NUV resolution, the FUV image is smoothed to a beam of FWHM = $7''.3$, and r.m.s noise of the smoothed map is 29.40 mag arcsec^{-2}. The overlaid FUV contour levels are 28.20, 27.33, 26.69, 25.94 and 25.19 mag arcsec^{-2}. North is up and east on the left. The scale of 1 arcmin is given, corresponding to 27 kpc if the distance of SQ is assumed to be 94 Mpc (H_0=70 Mpc^{-1} km^{-1} s). The red ellipse outlines the UV disk associated with NGC 7318b. **(b)** The same FUV contours overlaid on an B-band image. **(c)** The FUV image compared with the Hα (green contours, X99), HI (red contours, W02), CO from BIMA (blue contours, Gao & Xu 2000) and CO from IRAM (cyan contours, Lisenfeld et al. 2003).

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 MIR ($15\mu m$) source (Xu et al. 1999, hearafter 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, hearafter 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 HII region (SQ-B) is detect in both Hα (Arp 1973) and MIR (X99). Recently, Mendes de Oliveira et al. (2004, hereafter MdO04) discovered four intergalactic HII regions in a region north of the 'young tail', possibly associated with the stripped ISM of NGC 7319 (S01). The Hα observations (Arp 1973; Vilchez & Iglesias-Páramo 1998; Plana et al. 1999; S01) reveal numerous huge HII regions along several arms of NGC 7318b. Hunsberger et al. (1996), Iglesias-Páramo & Vilchez (2001), and Mendes de Oliveira et al. (2001) classified them as tidal dwarf galaxy candidates, though S01 argued that the crossing time of NGC 7318b ($\sim 10^7$ yrs) is too short for any tidal effects. There has been no estimate of the total star formation rate in SQ in the literature. Therefore it is not clear whether the overall star formation activity is enhanced by the interactions. Also, 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 GALEX (Martin et al. 2004). The GALEX observations are sensitive to very low levels of star formation averaged over $\sim 10^8$ yrs, the time scale of the tidal effects. This enables the first quantitative study on the overall star formation and its distribution in SQ. Comparisons between the UV, optical, HI, 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 2003-08-23, 2003-09-05 and 2003-09-06 in 5 orbits with total exposure time of 3327s. Data reduction was done using standard GALEX pipeline (IR0.2 calibration, Morrissey et al. 2004). The r.m.s noise is 27.65 mag arcsec^{-2} and 28.11 mag arcsec^{-2} in the FUV (1530Å) and NUV (2310Å), respectively. The UV magnitudes are in the AB system. The FWHM of the FUV beam is $4''.8$, and that of the NUV beam $7''.3$.

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 is that

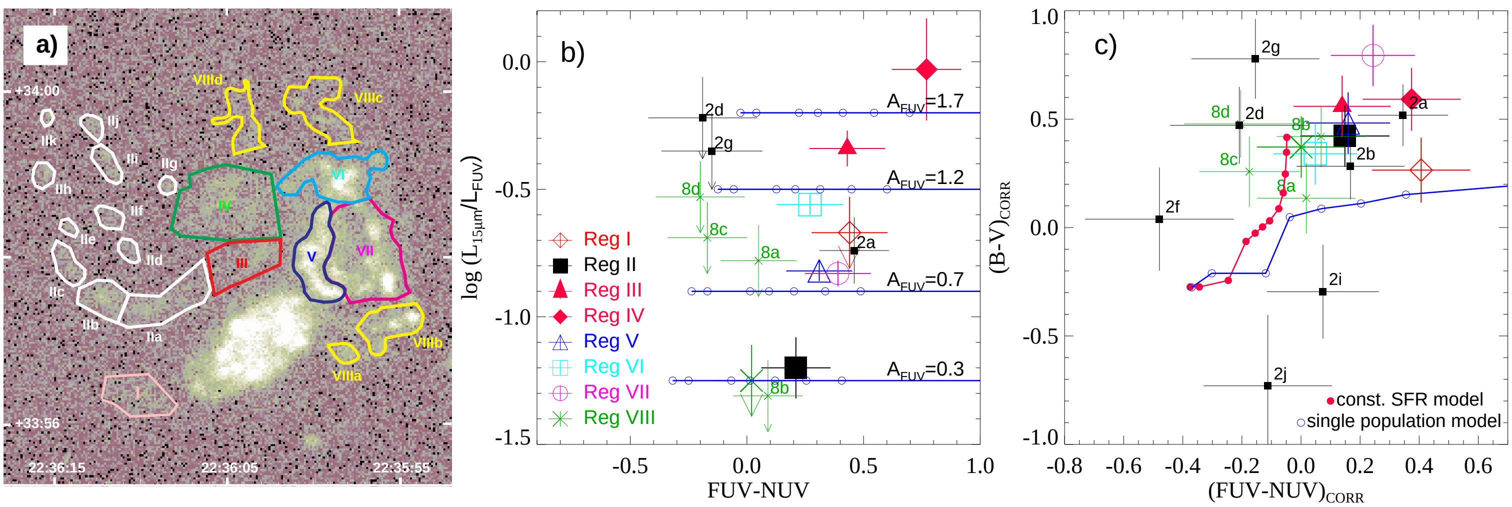

Fig. 2.— **a)** Definition of regions listed in Table 1. The boundaries are chosen according to FUV contours. **b)** $L_{15\mu m}/L_{FUV}$ v.s. FUV-NUV color plot. The FUV and NUV data are corrected only for the foreground Galactic extinction. The arrows indicate upper limits of the $15\mu m$ flux. The blue open circles linked by the blue lines are the single population models (PEGASE burst models) reddened by the corresponding A_{FUV}. From left to right, the models are with age t = 1, 2, 5, 20, 50, 100, 200, 500, 1000 Myr. **c)** B-V v.s. FUV-NUV color-color plot. Both colors are corrected for the Galactic and the internal extinction. The blue circles linked with blue line are the same single population model (without reddening) as plotted in Fig.2b. The red filled circles linked by red line are PEGASE models assuming constant SFR with ages of t = 1, 2, 5, 20, 50, 100, 200, 500, 1000, 2000, 5000, 10000 Myr.

there are large regions that do not coincide with significant optical light from the galaxies or optically detected tidal features. In the merger which gives rise to the Antennae (Hibbard et al. 2004) the UV emission is seen to follow the tidal tails and merger body closely, while being of $\sim 10^8$yr, of age simlar to the distributed UV emission in SQ.

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 the NGC 7318a is insignificant. This is because NGC 7318a has the optical apparence of an ordinary elliptical galaxy and no HII region or HI gas in this area is likely to be associated with it (M97; S01). The UV disk, with a physical size of $\sim$ 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 HI gas in this region which has the same redshift of NGC 7318b (W02). This agrees with the results of Thilker et al. (2004) who found that the UV emission regions in outer disk of M83 are typically associated with HI structures. The north tip of the disk goes beyond the HI 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 Sy2 nucleus of NGC 7319 is faint in the UV, indicating very high extinction within the AGN, consistent with the Sy2 classification. Both the 'young tail' and the 'old tail' are detected. The 'young tail' looks more like a 'loop' in the UV image. Compared to the optical tail, it extends further in the northeast direction and includes all the 4 intergalactic HII regions found by MdO04. The UV emission within the NGC 7319 disk shows a disturbed morphology. It is interesting to note that no HI gas has been detected in 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 Hα 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. 2004). The FUV magnitude, the FUV-NUV color and the B-V color in Table 1 are corrected for the foreground Galactic extinction (E(B-V)=0.079 and the extinction curve of Cardelli et al. 1989). For regions detected in ISOCAM 15μm map (X99), the internal extinction is determined using the luminosity ratio $\log(L_{15\mu m}/L_{FUV})$ according to the following formulae:

$$Y = \log(L_{IR}/L_{FUV}) = \log(L_{15\mu m}/L_{FUV}) + 1.04, \quad (1)$$

$$A_{FUV} = -0.033\,Y^3 + 0.352\,Y^2 + 1.196\,Y + 0.497. \quad (2)$$

The relation $\log(L_{IR}) = \log(L_{15\mu m}) + 1.04$ is taken from Chary & Elbaz (2001). Eq. (2) is taken from Buat et al. (2004). Other regions are either undetected or outside the ISOCAM $15\mu m$ map. For them the internal extinction is estimated using the average HI column density (W02) and the dust-to-gas ratio of the solar neighborhood ($\tau_B = 5.8\ 10^{-22}$ atoms^{-1} cm^2, Savage and Mathis 1979). The foreground screen model and a modified Calzetti attenuation curve (Buat et al. 2004) are assumed. For the extinction estimated using the HI, the error is assumed to be 100%. Estimates of the internal extinction of Reg. VI (SQ-A) using the MIR-to-FUV ratio and using the HI column density, respectively, are found to be consistent with each other. 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 Fioc & 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 (Reg. VI): The SFR of 1.34 ± 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}) by X03. On the other hand, the extinction estimated from the MIR-to-FUV ratio, $A_{FUV} = 0.76 \pm 0.06$, is significantly lower than that indicated by the Balmer decrement ($A_{H\alpha} \sim 0.6 - 2$). This suggests that O stars and B stars which are responsible for the ionizing and non-ionizing UV radiation, respectively, have different distributions relative to the dust. The extinction corrected B-V color suggests an underlying stellar population of ~ 500 Myr, consistent with the results of Gallagher et al. (2001).

Star formation in regions related to NGC 7319: These include Reg. I, II, III, and IV. Among the net SFR of 1.98 ± 0.58 $M_\odot$ yr^{-1}, 68% is contributed by the disk (Reg. IV), and 15% from the 'young tail' (Reg. II). There is a disk/tidal-tail gradient among the undereddened UV colors of Reg. 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 Reg. I (old tail) are consistent with a single population of age $t \simeq 10^{8.5\pm0.4}$ yrs, somewhat younger than that estimated by S01 from dynamic arguments (6–12 $\times10^8$ yrs).

Reg. II includes 11 subregions. IIa, IIb and IIc correspond to the optical tail. The age of the UV population in IIa and IIb is $\sim 10^8$ yrs while that of the optical population is $\sim 5\ 10^8$

yrs, 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 ($\sim 10^7$ yrs). It is outside our B and V image. The extragalactic HII regions found by MdO04 are also in Reg. II. IIi (c and d in MdO04) shows very young ages in both UV color and optical color ($\sim 10^6$ yrs), consistent with the EW(Hα) result of MdO04. IIj, which is north of IIi and is not in the list of MdO04, shows similar properties as IIi. The UV population of IIe (b in Md004) has an age of $\log(t) = 7.7 + / - 0.7$, older than that estimated by MdO04 (5.6 Myr) from EW(Hα). In the UV image these subregions, together with other subregions which are discovered for the first time, form a loop-like structure. Given that many of these subregions were also detected in other bands (e.g. optical and Hα) and available redshift data (S01; MdO04) are consistent with they all having the same redshift, this structure is very likely real. M97 suggested that the young tail is triggered by a high velocity ($\sim$ 700 km/sec) passage of NGC 7320c through NGC 7319 1.5 10^8 yrs 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/N7320c encounter must have occured $\gtrsim 5\ 10^8$ yrs 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. Also the 'UV loop', on the other side of NGC 7319 with regard to NGC 7318a, looks very similar to the 'counter tidal loop' found frequently in the dynamic simulations of galaxy-galaxy interactions (see, e.g., Fig.2 of Toomre & Toomre 1972, t=2 10^8 yr).

Star formation in regions related to NGC 7318b: These include Reg. V, VII, and VIII. The peaks of the UV emission in Reg. V correspond to a chain of HII 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±0.25 $M_\odot$ yr^{-1}. This is very close to the SFR of the Milky Way ($\sim 4 \pm 2\ M_\odot$ yr^{-1}, Mezger 1988), a normal Sbc galaxy. Reg. VIII includes 4 subregions, VIIIa and VIIIb are in the south end of the UV disk, and VIIIc and VIIId in the north end. They are 30 — 40 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. (2004). Whether the remarkable size of this UV disk, the peculiar morphology of the 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 yrs ago (X03), is an interesting subject for future studies. The UV and optical colors of VIIIa are consistent with a single population of $\sim 10^8$ yrs.

Summary remarks: Every time when SQ is observed in a waveband for the first time, it reveals new, spectecular phenomona 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 inference to the interaction induced star formation in multi-galaxy systems which may play important roles in the early universe.

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Table 1. Star Formation Properties in SQ Regions

(1) Name	(2) Reg.	(3) FUV mag	(4) $\log(L_{FUV})$ $L_\odot$	(5) SFR $M_\odot$ yr^{-1}	(6) FUV-NUV mag	(7) $\log(t_{UV})$ yr	(B m
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
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
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
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
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
SQ-A	VI	17.32±0.10	9.84±0.05	1.335±0.156	0.27±0.14	7.4±0.6	0.44
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
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
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 corrected for the foreground Galactic extinction. Column (4) — extinction corrected FUV luminosity (c and the internal extinction). The error includes the uncertain of the extinction correction. Column (6) — Galactic extinction. Column (7) — stellar population age derived from extinction corrected UV color, usin The error includes the uncertain of the extinction correction. Column (8) — optical color corrected on Column (9) — stellar population age derived from extinction corrected optical color, using the single pop

[a]Contribution from the AGN is subtracted from the UV, optical and MIR flux densities.