PHYSICAL CONDITIONS AND STAR FORMATION ACTIVITY IN THE INTRAGROUP MEDIUM OF STEPHAN’S QUINTET\textsuperscript{1,2,3}

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ABSTRACT

New multiband observations of the famous compact group of galaxies Stephan’s Quintet (SQ) are presented and analyzed. These include far-infrared (FIR) images at 60 and 100 \ µm (ISOPHOT C100 camera), radio continuum images at 1.4 GHz (VLA B configuration) and 4.86 GHz (VLA C configuration), and long-slit optical spectrographs (Palomar 200” telescope). With these new data, we aim to learn more about the X-ray/radio ridge in the middle of the intragroup medium (IGM) and the IGM starburst SQ-A, both of which are likely to be caused by the high-speed collision (\sim 900 km s\(^{-1}\)) between the intruder galaxy NGC 7318b (\(v = 5700 \text{ km s}^{-1}\)) and the IGM (\(v = 6600 \text{ km s}^{-1}\)). We found that the radio ridge has a steep non-thermal spectral index (\(\alpha = 0.93 \pm 0.13\)) and an extremely low FIR-to-radio ratio index (\(q < 0.59\)). Its IR emission can be explained in terms of collisional heating of dust grains by shocked gas. The minimum-energy magnetic field strength is \(H_{\text{min}} \approx 10 \mu\text{G}\). The long-slit spectra of sources in the ridge have typical emission-line ratios of shock-excited gas. The very broad line widths (\(\geq 1000 \text{ km s}^{-1}\)) and the fact that in some cases more than two velocity systems were detected along the same line of sight provide further evidence for an ongoing collision along the ridge. The IGM starburst SQ-A has a radio spectral index \(\alpha = 0.8 \pm 0.3\) and a FIR-to-radio ratio index \(q = 2.0 \pm 0.4\), consistent with those of star-forming regions. The optical spectra of two sources in this region, M1 (\(v = 6600 \text{ km s}^{-1}\)) and M2 (\(v = 6000 \text{ km s}^{-1}\)), have typical line ratios of H\textsc{ii} regions. Both M1 and M2 have metallicity slightly higher than the solar value. The star formation rate estimated from the extinction-corrected H\textsc{a} luminosity of SQ-A is 1.45 \(M_\odot\) yr\(^{-1}\), of which 1.25 \(M_\odot\) yr\(^{-1}\) is due to the \(v = 6600 \text{ km s}^{-1}\) component and 0.20 \(M_\odot\) yr\(^{-1}\) to the \(v = 6000 \text{ km s}^{-1}\) component.

Subject headings: galaxies: active — galaxies: interactions — galaxies: ISM — galaxies: starburst — infrared: galaxies — intergalactic medium

On-line material: color figures

1. INTRODUCTION

There is a resurgent enthusiasm recently on the investigations of the historically famous Stephan’s Quintet (hereafter SQ), a multigalaxy system discovered by the National Radio Astronomy Observatory in the late nineteenth century (Stephan 1877). As summarized in Sulentic et al. (2001), many new observational data have recently become available for this intriguing source. In particular, a few new frequency windows have been opened to astronomical observations in this space era. The X-ray observations using ROSAT (Sulentic, Pietsch, & Arp 1995; Saracco & Ciliegi 1995; Pietsch et al. 1997; Sulentic et al. 2001) and Chandra (Trinchieri et al. 2003), infrared observations using the Infrared Space Observatory (ISO; Xu, Sulentic, & Tuffs 1999; Sulentic et al. 2001), and very high angular resolution optical images using the Hubble Space Telescope (HST; Gallagher et al. 2001) have revealed intriguing new features in this fascinating galaxy group. Particularly, an unusual IR source was discovered by Xu et al. (1999) in the intragroup medium (IGM) of SQ, located more than 20 kpc away from any neighboring galaxy centers. The IR source, named source A (hereafter SQ-A) by Xu et al. (1999), is apparently associated with a starburst triggered by the high-speed collision (relative velocity \(\sim 1000 \text{ km s}^{-1}\)) between the intruder galaxy NGC 7318b and the IGM. It is the location in the IGM that makes the starburst so unusual. This is also the first example of an ongoing starburst triggered by collisions of such high speed, although evidence for a poststarburst was found previously by Kenney et al. (1995) in the high-speed colliding system NGC 4438/4439.

Another outstanding feature in SQ is the large-scale shock front (\(\sim 40 \text{ kpc}\)) in the IGM between NGC 7319 and NGC 7318b, first discovered by Allen & Hartsuiker (1973)
as a radio emission ridge in the 21 cm Westerbork radio continuum map and later confirmed by the VLA observations of van der Hulst & Rots (1981) and Williams, Yun, & Verdes-Montenegro (2003). The high-resolution X-ray maps of SQ (Pietsch et al. 1997; Sulentic et al. 2001; Trinchieri et al. 2003) show an X-ray emission ridge at almost exactly the same position, making it very certain that this ridge is the signature of a shock front. Given the fact that the relative velocity between the gas-rich intruder galaxy NGC 7318b and the rest of the group is ~900 km s\(^{-1}\) and that there is widely spread cold H I gas in the IGM (Shostak, Sullivan, & Allen 1984; Williams et al. 2002), it is indeed expected that such a shock must be happening in the region where the cold gas associated with the intruder collides with the cold gas in the IGM.

Xu et al. (1999) argued strongly that the two phenomenal events, namely, the ongoing IGM starburst and the large-scale shock, are intimately related with each other: the starburst is very likely triggered by the same collision that triggered the shock. In this paper we present new observations in the infrared, radio continuum, and optical spectroscopy for SQ. With these new data and data found in the literature, we aim to better constrain the physical conditions in the IGM, particularly in the shock front region and in SQ-A, and investigate further the physical mechanism linking the two events. The paper is organized as follows: After this introduction, the new observations are presented in § 2–4. In § 5 we study the physical conditions in the IGM. In § 6 we investigate the triggering mechanism for the IGM starburst SQ-A. Section 7 is devoted to a discussion, and the conclusions are presented in § 8. We assume that the distance of SQ is 80 Mpc and the distance of the foreground interloper NGC 7320 is 10 Mpc.

### 2. MAPPING OF IR EMISSION WITH ISO

#### 2.1. Observations

The mapping observations of SQ were carried out on 1996 May 23 using ISOCAM and ISOPHOT on board ISO (Kessler et al. 1996). The total on-target time for the ISOCAM maps (at 15 and 11.4 \(\mu\)m) is 33 ks and for the ISOPHOT maps (at 60 and 100 \(\mu\)m) is 14 ks. These maps are among the most sensitive observations ever made by ISO. The 15, 11.4, and 60 \(\mu\)m maps have already been published in Xu et al. (1999) and Sulentic et al. (2001). In this paper we present the 100 \(\mu\)m map, which is the last product from our ISO project. In Table 1 we summarize the ISO observations.

| Camera          | Array Size | Filter | \(\lambda\) (\(\mu\)m) | \(\delta\lambda\) (\(\mu\)m) | Detector Pixel (arcsec) | Sampling Step (arcsec) | Map Size (arcmin) | rms \(\text{rms} = \text{rms} \times 10^{-1}\) (M\(\text{Jy}\) sr\(^{-1}\)) | rms \(\text{rms} \times 10^{-0}\) (M\(\text{Jy}\) beam\(^{-1}\)) | Calibration Error (%) |
|-----------------|------------|--------|------------------------|-----------------------------|-------------------------|----------------------|-------------------|------------------------------------------------------------|------------------------------------------------|-----------------------|
| ISOCAM LW........| 32 \times 32 | LW8    | 11.4                   | 2.3                         | 6 \times 6               | 6 \times 6           | 5 \times 12        | 0.083                                                      | 0.22                                                          | ~20                   |
| ISOPHOT C100.....| 3 \times 3   | C60    | 60.8                   | 23.9                        | 45 \times 45             | 15 \times 15         | 6 \times 13        | 0.33                                                       | 14                                                            | ~20                   |
| ISOPHOT C100.....| 3 \times 3   | C100   | 103.5                  | 43.6                        | 45 \times 45             | 15 \times 15         | 6 \times 13        | 0.40                                                       | 16                                                            | ~20                   |

* Beam areas are calculated assuming Gaussian beams of FWHM of 10\(\prime\) for the ISOCAM maps (undersampled) and FWHM of 40\(\prime\) for the ISOPHOT maps (oversampled).
the final 100 and 60 μm maps finds total flux densities (and
rms errors) of SQ of \( f_{100, \mu m} = 2.22(\pm 0.03) \) Jy and
\( f_{60, \mu m} = 1.07(\pm 0.03) \) Jy, in good agreement with the IRAS
values of \( f_{100, \mu m} = 2.54 \pm 0.36 \) Jy and \( f_{60, \mu m} = 0.88 \pm 0.09 \)
Jy. From these comparisons, the IRAS values are consistent
with the ISO values to within 20%. In what follows we
adopt a conservative estimate of 20% for the systematic
calibration uncertainty of the ISO data.

2.2. Results

In Figure 1 we present the images of the 100 and 60 μm
maps. In both maps the background is quite smooth and the
noise behaves normally. No obvious artifacts can be seen in
the images except for near the edges. The emission in both
maps is dominated by two sources, one associated with the
Seyfert galaxy NGC 7319 (on the right), the other with the
foreground galaxy NGC 7320. These two galaxies were
marginally resolved and detected in the 60 μm IRAS HIRES
map (Allam et al. 1996). In the other three IRAS bands (12,
25, and 100 μm), only NGC 7319 was detected in the IRAS
HIRES study of Allam et al. (1996).

In both ISOPHOT 100 and 60 μm maps, the source asso-
ciated with NGC 7319 is slightly elongated along the scan
direction (P.A. = 167°), with the size (FWHM) along the
major axis being 48″ and 54″, respectively, and the minor/
major axis ratio being 0.78 and 0.61, respectively. This
might indicate that, in addition to the IR emission of the
Seyfert 2 nucleus that dominates the mid-infrared (MIR)
emission of NGC 7319 (Xu et al. 1999; Sulentic et al. 2001),
the dust in the host galaxy may contribute significantly to
the far-infrared (FIR) emission. The Hα arm on the north
of the nucleus (Xu et al. 1999; see also Fig. 6 below), where
massive molecular gas was also detected (Yun et al. 1997;
Gao & Xu 2000), may indeed be active star formation

![ISOPHOT Images](image)
regions in the disk of NGC 7319 and therefore be bright in the FIR. On the other hand, it cannot be ruled out that the elongation is caused by some residual transient effects in the ISO maps, given the coincidence with the scan direction. Future observations with higher angular resolutions (e.g., using SIRTF-MIPS) will help to distinguish these two possibilities.

In Figure 2 contours of the 100, 60, 15, and 11.4 μm maps are overlaid on the 15 μm image. Sources detected in the 15 μm map are labeled according to Xu et al. (1999). Comparisons with ISOCAM maps show that the IGM starburst SQ-A, as well as the main body of the galaxy pair NGC 7318a/b, is clearly detected in the longer wavelength ISOPHOT maps. Another weaker IGM starburst discovered in the ISOCAM 15 μm map (Xu et al. 1999), source B (hereafter SQ-B), also appears to be detected in both the 100 and 60 μm maps. However, its ISOPHOT flux densities are highly uncertain (at about a factor of 2 level) because SQ-B is located on a background plateau as a result of a more extended (but at the same time rather structured) low-emission region and therefore it is difficult to subtract the background accurately.

It is always difficult to measure flux densities for individual sources in a crowded field such as SQ. This problem becomes even more severe in the ISOPHOT maps, where the angular resolutions are poor (~40′′). Indeed, the ISOPHOT flux densities of the weaker sources such as SQ-A and NGC 7318a/b had to be measured on the residual maps after subtracting the two bright sources NGC 7319 and NGC 7320. In this

![Figure 2](image-url)
procedure, the two bright sources are approximated by two
two-dimensional Gaussians in each of the ISOPHOT maps
and are then subtracted from the map. In Figure 3 we present
the contours of the residual 100 and 60 μm maps,
respectively. Given the surface brightness distributions of NGC
7319 and NGC 7320 in the higher resolution ISOCAM maps,
the two-dimensional Gaussian model should be a good
approximation. Nevertheless, the ISOPHOT flux densities
of SQ-A and NGC 7318a/b have large uncertainties due to
the sensitive dependence on the subtraction of brighter
sources.

In Table 2 we list the IR flux densities of the individual
sources measured from the ISO maps. Except for the flux
densities presented with brackets denoting the high uncer-
tainties (see discussion above), the errors of the measure-
ments are on the order of 20%, mostly as a result of the
adopted (rather conservative) calibration uncertainty (see
§ 2.1). The errors of those flux densities with brackets can
easily be 50% or more. The coordinates of the galaxies
are taken from NED, while the positions of the ISOCAM

![Fig. 3.—Contour maps of the 100 (left) and 60 μm (right) emission after the subtraction of NGC 7319 and NGC 7320, overlaid on the 15 μm image. The contour levels for the 100 μm map (left) are (2, 2.8, 4, 5.6) × 0.4 MJy sr⁻¹; for the 60 μm map (right) they are (2, 2.8, 4, 5.6) × 0.33 MJy sr⁻¹.](image)

| Name                   | R.A. (J2000.0) | Decl. (J2000.0) | f11 μm (mJy) | f15 μm (mJy) | f60 μm (mJy) | f100 μm (mJy) | Note       |
|------------------------|---------------|----------------|--------------|-------------|-------------|--------------|------------|
| NGC 7317               | 22 35 52.0    | +33 56.41      | 1.6          | 2.2         | ...         | ...          | E galaxy   |
| Shock and NGC 7318a/b  | 22 35 57.6    | +33 57.57      | 23.9         | 19.2        | (76)        | (230)        | Shock and galaxy pair |
| NGC 7319               | 22 36 03.5    | +33 58.33      | 54.5         | 76.3        | 275         | 350          | Seyfert 2 galaxy |
| NGC 7320               | 22 36 03.5    | +33 56.54      | 46.7         | 27.3        | 260         | 609          | Foreground galaxy |
| SQ-A                   | 22 35 58.7    | +33 58.50      | 10.9         | 10.9        | (60)        | (106)        | IGM starburst |
| SQ-B                   | 22 36 10.2    | +33 57.21      | 0.9          | 1.7         | (13)        | (21)         | IGM starburst |
| SQ-C                   | 22 36 02.7    | +33 59.56      | 3.3          | 0.6         | ...         | ...          | Star       |
| SQ-D                   | 22 36 00.1    | +33 55.52      | (0.2)        | 0.7         | ...         | ...          | Background galaxy |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

* These three regions are grouped together because they can hardly be separated from each other in the ISOPHOT maps (Fig. 3).

* The ISOPHOT flux densities of SQ-A were measured in the region outlined by the northwest peak in the residual 60 μm map (Fig. 3, right).
detected massive molecular gas in this region. In other places, it might be powered by either stars stripped from galaxies during previous close encounters between SQ members (Moles, Sulentic, & Marquez 1997; Sulentic et al. 2001) or the diffuse X-ray–emitting gas (Trinchieri et al. 2003). This will be a very interesting problem for future, more sensitive IR observations.

The early-type galaxy NGC 7317, detected by ISOCAM at both 15 and 11.4 µm, was not detected by ISOPHOT, nor were ISOCAM sources C (a star in the north of SQ) and D (a background galaxy in the south of SQ).

3. RADIO CONTINUUM OBSERVATIONS WITH THE VLA

3.1. Observations and Data Reduction

There have been several interferometric radio continuum observations of SQ in the literature (Allen & Hartsuiker 1973; van der Hulst & Rots 1981; Williams et al. 2002; Xanthopoulos et al. 2002). With new high-sensitivity, high angular resolution VLA imaging observations in two bands (1.40 and 4.86 GHz), we aim to constrain the spectral indices of individual sources. We also try to detect the polarization, particularly in the shock front region, in an attempt to constrain the magnetic field.

In order to image the radio continuum brightness, polarization, and spectral index distributions of SQ, we observed SQ with the VLA at 1.4 GHz in B configuration for 5 hr on 1999 November 15 and at 4.86 GHz in C configuration for 8 hr on 2000 April 27. During both observations, the source 3C 48 \((S_{1.4 \text{GHz}} = 16.19 \text{ Jy}, S_{4.86 \text{GHz}} = 5.52 \text{ Jy};\) Baars et al. 1977) was used to calibrate the fringe amplitudes to the updated VLA flux density scale. The polarization position angles were determined from 3C 138, and the nearby source J2236+284 was used as the phase calibrator.

Preliminary total intensity (Stokes I) images were made and cleaned by the AIPS task IMAGR. To maximize surface brightness sensitivity and at the same time minimize the synthesized sidelobes, we used tapered uniform weighting with Gaussian amplitude tapering to 30% at 25,000 wavelengths and truncated at 45,000 wavelengths. This strong taper yields a large synthesized beam area having the high surface brightness sensitivity of natural weighting. The nearly uniform weighting below 25,000 wavelengths reduces the dirty beam sidelobes that natural weighting would produce because the central part of the VLA synthetic aperture would be “overilluminated.” Then the clean components from these images were subtracted from the \((u, v)\) data. All residual visibilities having amplitudes much larger than the rms noise were flagged, and the clean components were added back to the edited data set. This procedure removes low-level interference and other problems that cause individual visibilities to disagree significantly with the data set as a whole. New images of 1024 pixels times 1” pixel\(^{-1}\) on a side were made, cleaned, and restored with 60” FWHM circular Gaussian beams, and the final images were corrected for primary-beam attenuation. The rms noise levels are \(\sigma \approx 25 \mu\text{Jy beam}^{-1}\) at 1.40 GHz and \(\sigma \approx 17 \mu\text{Jy beam}^{-1}\) at 4.86 GHz. Matching Stokes \(Q\) and \(U\) images were also made, and they have somewhat lower noise levels. No linearly polarized emission brighter than 50 \(\mu\text{Jy beam}^{-1}\) was found in any component of SQ at either 1.40 or 4.86 GHz.

3.2. Radio Continuum Images

In Figure 4 we present the total intensity contour maps of the 1.40 and 4.86 GHz images, both overlaid on an \(R\)-band CCD image (Xu et al. 1999).

The following radio sources are visible in these maps, and their fitted parameters are listed in Table 3:

1. There is a strong steep-spectrum source whose centroid at \(\alpha = 22^h36^m03^s55, \delta = +33^\circ58^\prime32^\prime\prime6\) (J2000.0) overlaps the optical nucleus of the Seyfert 2 galaxy NGC 7319 at \(\alpha = 22^h36^m03^s56, \delta = +33^\circ58^\prime33^\prime\prime2\). We fitted this source
with elliptical Gaussians and deconvolved the 6\,\arcsec restoring beams to obtain Gaussian approximations to the source FWHM major axis, minor axis, and position angle at both frequencies: 4.5' x 16' in P.A. = 29\,\degree east of north in the 1.40 GHz map, 4.5' x 1.5' in P.A. = 27\,\degree in the 4.86 GHz map. These sizes and orientations are reliable even though the deconvolved source size is smaller than the beam because the signal-to-noise ratio of this source is so high in our images. They are consistent with the linear triple structure found in higher resolution VLA images at 3.6, 6, and 20 cm (Aoki et al. 1999). The precise agreement of our 1.40 GHz integrated flux density with theirs (28.5 mJy in both cases) indicates that there can be very little extended emission surrounding the triple. The orientation of the radio triple is nearly parallel to the H\alpha-[N\,\text{ii}] emission line region visible in Figure 2 of Xu et al. (1999). This phenomenon is common in Seyfert galaxies and suggests that the radio jets are brightening the line-emitting gas by compression.

2. There is a weak radio source in NGC 7318a, the early-type galaxy in the binary system NGC 7318a/b. This radio source is unresolved (FWHM < 4\,\arcsec) in our images and centered on \(\alpha = 22^h36^m00^s, \delta = +33^\circ59^\prime00^\prime\), precisely coincident with the optical nucleus at \(\alpha = 22^h35^m56^s7.2, \delta = +33^\circ57^\prime56^\prime0\) (Klemola, Jones, & Hanson 1987). The source has been detected previously by van der Hulst & Rots (1981) and Williams et al. (2002) at 1.40 GHz. Our measurement of the S_{1.4\,\text{GHz}} (0.95 \pm 0.05 \text{mJy}) is slightly (~2 \sigma) lower than that of Williams et al. (2002) (1.4 \pm 0.2).

3. There is a radio ridge at \(\alpha \approx 22^h36^m00^s\), which extends north-south from \(\delta \approx +33^\circ57^\prime10^\prime\) to \(\delta \approx +33^\circ58^\prime40^\prime\) and then bends west and terminates near \(\alpha = 22^h35^m56^s, \delta = +33^\circ59^\prime15^\prime\) (Allen & Hartsuiker 1973; van der Hulst & Rots 1981; Williams et al. 2002). The radio ridge is coextensive with the X-ray ridge (Pietsch et al. 1997), the ridge of the high-redshift (6600 km s\textsuperscript{-1}) component of the H\alpha-[N\,\text{ii}] emission (Xu et al. 1999), and the FIR emission shown in Figure 3. With a very faint optical continuum counterpart, the ridge appears to delineate a shock front containing relativistic electrons, magnetic fields, hot thermal electrons, ionized gas, and cool dust. The 1.4 GHz flux density, S_{1.4\,\text{GHz}} = 34.7 \pm 3.5 \text{mJy}, is about 30\% lower than the result of Williams et al. (2002) obtained using their lower resolution image, which is S_{1.4\,\text{GHz}} = 48 \pm 7 \text{mJy}, indicating that our high-resolution B configuration image may be missing about 13 mJy of flux from the ridge.

4. The relatively weak and diffuse radio peak near \(\alpha = 22^h35^m58^s8.8, \delta = +33^\circ58^\prime50^\prime\) overlaps the IGM starburst SQ-A just north of the bend in the ridge. Its 1.40 and 4.86 GHz flux densities were estimated by fitting Gaussians to SQ-A above base planes fitted to the surrounding ridge emission.

5. The binary radio source (called SQ-R in Table 3), with the stronger component at \(\alpha = 22^h36^m01^s01, \delta = +33^\circ59^\prime12^\prime3\) and the weaker component at \(\alpha = 22^h36^m02^s39, \delta = +33^\circ59^\prime02^\prime\), is almost certainly the cosmologically distant background source seen in projection behind SQ (van der Hulst & Rots 1981; Williams et al. 2002). It has no optical counterpart brighter than 29 mag arcsec\textsuperscript{-2} (Williams et al. 2002), nor any IR counterpart in the ISO images. The 1.40 GHz flux density is in excellent agreement with Williams et al. (2002).

6. The weak IGM starburst SQ-B (near the eastern boundary of the images) is marginally detected in both 1.40 and 4.86 GHz maps.

The flux densities of these sources are listed in Table 3. Their total 1.40 GHz flux is 76.5 mJy, somewhat smaller than the S_{1.4} = 93 \pm 4 \text{mJy} from the D configuration NVSS image, so our B configuration image may be missing up to 16.5 mJy of diffuse flux. A comparison with the total flux density (S_{1.4} = 96 \pm 15 \text{mJy}) from the C and D configuration image of Williams et al. (2002) leads to a similar conclusion.

In Figure 5 we present the contour map of the spectral index \(\alpha = \log(S_{1.4\text{GHz}}/S_{86\text{GHz}})/(\log(4.86/1.4))\) overlaid on the ISO/CAM 15 \text{$\mu$m} map. It should be noted that there is little effect of the missing flux on the spectral index analysis because (1) the \((u,v)\) plane coverages and synthetic beams of the two images are very similar and therefore about the same fraction of flux is missed in the two bands, and (2) the flux missed is mostly in the diffuse emission that contributes little to the flux ratios of the relatively high surface brightness regions where the spectral index analysis is confined. Both the 1.40 and 4.86 GHz maps were smoothed to a common Gaussian beam of FWHM = 10\,\arcsec, the beam size of the ISO/CAM map, before the calculation of the spectral index. Only pixels with \(s/\sigma > 2\) in both maps were included in the calculation. Both the background binary source and the strong source associated with the Seyfert 2 galaxy NGC 7319 have fairly normal spectral indices \(\alpha \sim 0.8\), and the radio source associated with NGC 7318a has a slightly flatter spectral index \(\alpha \sim 0.6\). A large part of the radio ridge associated with the shock front has \(0.7 < \alpha < 1.1\), typical for the synchrotron emission from relativistic electrons, while a small part of the ridge immediately south of SQ-A shows steep \((\alpha \sim 1.2)\) spectrum. It is interesting to note that, albeit not being plotted by the spectral index contours inTABLE 3

| Name         | R.A. (J2000.0) | Decl. (J2000.0) | S_{1.4\,\text{GHz}} (mJy) | S_{86\,\text{GHz}} (mJy) | Spectral Index (\alpha) | FIR/Radio Index (q) |
|--------------|----------------|----------------|---------------------------|--------------------------|------------------------|---------------------|
| Ridge        | 22 35 59.8     | +33 58 00      | 34.7 \pm 3.5              | 10.9 \pm 1.1             | 0.93 \pm 0.13          | <0.59               |
| NGC 7318a    | 22 35 57.6     | +33 57 56.0    | 0.95 \pm 0.05             | 0.44 \pm 0.03            | 0.62 \pm 0.07          | ...                 |
| NGC 7319     | 22 36 03.55    | +33 58 32.6    | 28.5 \pm 0.5              | 9.7 \pm 0.3              | 0.87 \pm 0.03          | 1.08 \pm 0.10       |
| SQ-A         | 22 35 58.8     | +33 58 30      | 0.8 \pm 0.2               | 0.3 \pm 0.1              | 0.8 \pm 0.3            | 2.0 \pm 0.4         |
| SQ-B         | 22 36 10.2     | +33 57 21      | 0.6 \pm 0.2               | 0.2 \pm 0.1              | 0.7 \pm 0.4            | 1.5 \pm 0.7         |
| SQ-R         | 22 36 00.1     | +33 59 12.3    | 10.3 \pm 1.0              | 3.7 \pm 0.4              | 0.85 \pm 0.12          | ...                 |

Note: Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

* The \(q\) (upper limit) is calculated using the ISOPHOT flux densities of a region including also NGC 7318a/b (Table 3).
Figure 5 because of low $s/\sigma$, this steep spectrum appears to extend to the northwest of SQ-A where diffuse X-ray (Trinchieri et al. 2003) and H$\alpha$ (Fig. 6) emission was detected. Since a steep-spectrum radio emission is usually associated with aging cosmic-ray electrons, its distribution...
Given the relatively large uncertainty, the $q$-value of SQ-A ($q = 2.0 \pm 0.4$) is consistent with normal star formation. For SQ-B, another starburst in the IGM of SQ, $q = 1.5 \pm 0.7$. This is substantially lower than the mean, although only at $\sim 1 \sigma$ significance level because of the large error bar. SQ-B has large uncertainties in both the FIR and the radio continuum flux densities, mainly because it is located on a background plateau as a result of a more extended (but at the same time rather structured) low-emission region. This makes not only the background subtraction difficult but also the boundaries of the emission associated with this source highly uncertain.

4. LONG-SLIT OPTICAL SPECTROSCOPY

4.1. Observations

Long-slit optical spectroscopic observations were made on 1999 September 21 (UT) using the Double Spectrograph mounted on the Cassegrain focus of the Palomar 200″ telescope. For the red channel (5600–8000 Å), 316 line mm$^{-1}$ grating mode (102 Å mm$^{-1}$) was chosen, and for the blue channel (3700–5400 Å), 600 line mm$^{-1}$ grating mode (71 Å mm$^{-1}$) was used. Two 1024 × 1024 CCD detectors, one for each channel, have pixel size of 24 μm. The slit is 128″ long and 2″ wide. The spectral dispersions for the red and blue spectra are 2.4 and 1.7 Å pixel$^{-1}$, respectively. Measured from the bright skylines, the FWHM spectral resolutions are 7.5 Å for the red channel and 4.6 Å for the blue. These correspond to velocity resolutions of 343 and 283 km s$^{-1}$ at H$\alpha$ and H$\beta$, respectively.

Observations were carried out along two slits: slit M and slit N (Fig. 6). Slit M is centered at $\alpha = 22^h35^m58^s17, \delta = +33^\circ58'50''$ (J2000.0), with a position angle of 128°. Slit N is centered at $\alpha = 22^h35^m59^s8, \delta = +33^\circ58'00''$ (J2000.0), with a position angle of 176°. Three exposures, each lasting for 20 minutes, were carried out for each slit orientation. The spectra derived from these individual exposures were co-added for each slit orientation during the data reduction, which was done using IRAF developed by the National Optical Astronomy Observatory.

The standard neon and hollow cathode lamp spectra were taken before and after each source observation for the purpose of wavelength calibration. For each red or blue spectrum, about 20–25 bright emission lines with accurately known wavelengths were used to determine a wavelength solution with an accuracy of better than 0.2 Å. The flux calibration was done via observations of the standard stars BD +28°4211 and G191-B2B from Oke (1990) in a 4′ wide slit. The night was not strictly photometric, with some thin cirrus clouds and a variable seeing between 1″2 and 1″5. While the relative flux calibration across a spectrum should be quite good, the absolute flux calibration is less certain, probably not much better than 30%.

In Figure 7 we present the four spectrographs (two slits, two channels). Along slit M and slit N, significant signals were detected around four (M1, M2, M3, M4) and five positions (Na, Nb, Nc, Nd, Ne), respectively. They are listed in Table 4. The approximate positions of these sources are also marked in Figures 6 and 7. For each source, we have defined an aperture size, given in the last column of Table 4. This aperture was used to extract a one-dimensional spectrum. The resulting blue and red spectra of these sources are plotted in Figure 8 for slit M and Figure 9 for slit N.

4.2. Emission Lines

In Table 5 we list the following measured quantities for the detected lines:

1. The corresponding redshift in km s$^{-1}$.
2. Velocity dispersion (in km s$^{-1}$).
3. Line flux in 10$^{-15}$ ergs cm$^{-2}$ s$^{-1}$.

In Figure 10 we present close-up plots of the following lines: [O ii] $\lambda$3727, H$\beta$, [O iii] $\lambda$4959/$\lambda$5007, [O i] $\lambda$6300, H$\alpha$/[N ii] $\lambda$6548/$\lambda$6583, [S ii] $\lambda$6717/$\lambda$6731.

Fig. 7.—Spectrographs of the IGM star formation regions and of the shock front in SQ (see Fig. 6 for the locations of slit M and slit N). The approximate positions are marked for redshifted emission lines of [O ii] $\lambda$3727, H$\beta$, [O iii] $\lambda$4959/$\lambda$5007, [O i] $\lambda$6300, H$\alpha$ (including [N ii] $\lambda$6548/$\lambda$6583), and [S ii] $\lambda$6717/$\lambda$6731. Emission regions along slit M and slit N are labeled (near H$\alpha$/[N ii] lines) in the same way as in Fig. 6.
TABLE 4
Spectroscopic Sources along the Two Slits

| Source ID | R.A. (J2000.0) | Decl. (J2000.0) | Aperture (arcsec) |
|-----------|----------------|----------------|------------------|
| M1        | 22 35 59.18    | 33 58 45.3     | 9 x 2            |
| M2        | 22 35 58.11    | 33 58 55.6     | 15 x 2           |
| M3        | 22 36 01.90    | 33 58 18.8     | 18 x 2           |
| M4        | 22 35 56.54    | 33 59 10.9     | 8 x 2            |
| Na        | 22 35 59.77    | 33 58 01.8     | 14 x 2           |
| Nb        | 22 35 59.91    | 33 57 36.8     | 8 x 2            |
| Ne        | 22 35 59.62    | 33 58 26.2     | 8 x 2            |
| Nd        | 22 35 59.50    | 33 58 47.9     | 8 x 2            |
| Ne        | 22 36 00.02    | 33 57 17.4     | 15 x 2           |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

4.3. Notes for Individual Sources

The individual sources are described as follows:

M1: the brightest source, near the center of the IGM starburst associated with the MIR source SQ-A (Xu et al. 1999). The line emission is predominantly from the 6600 km s\(^{-1}\) component (component 1 in Table 5). The most conspicuous evidence for the second component (component 2 in Table 5), centered at ~5900 km s\(^{-1}\), is the second peak of the [O\(\text{III}\)] line. This second component also shows up in the [O\(\text{II}\)] 5007 line and the [S\(\text{II}\)] 6716 line.

M2: the second brightest source, also associated with the MIR source SQ-A. However, different from M1, the line emission of this source is from the 6600 km s\(^{-1}\) component. The emission from the 6600 km s\(^{-1}\) component is not detected here. This is in good agreement with Moles, Marquez, & Sulentic (1998).

M3: a relatively faint source, located within the H\(\alpha\) bridge linking the shock front and the Seyfert 2 nucleus of NGC 7319. Only one component centered at ~6450 km s\(^{-1}\) is detected. The marginal detection of the [S\(\text{II}\)] 6716 line at 6600 km s\(^{-1}\) is deemed unreliable because of the large errors associated with the skyline subtraction. The high \(I([\text{N}\text{II}])/I(\text{H}\alpha)\) ratio (0.90) suggests that the H\(\alpha\) bridge is either a cooling flow (Heckman et al. 1989) or gas bowshocked by an AGN jet (Aoki et al. 1999).

M4: another weak source, associated with a diffuse emission region in the periphery of the IGM starburst. The \(I([\text{S}\text{II}])/I(\text{H}\alpha)\) ratio indicates that the emission is shock excited rather than radiatively excited (Dopita & Sutherland 1995). Apparently it is associated with source 5 in the Chandra image (Fig. 1 of Trinchieri et al. 2003).

M5: located near the center of the shock front. Three velocity systems (6800, 6100, and 6400 km s\(^{-1}\)) are detected in the emission lines, with the 6100 km s\(^{-1}\) component dominating the H\(\alpha\), [N\(\text{II}\)], [S\(\text{II}\)], and [O\(\text{II}\)] lines and the 6800 km s\(^{-1}\) component dominating the high-excitation [O\(\text{III}\)] line. The very broad [O\(\text{I}\)] 6300 line \((\delta V = 1134 \text{ km s}^{-1})\), which is the only line showing the 6400 km s\(^{-1}\) component, may well be due to the blending of the same line in the 6100 and 6800 km s\(^{-1}\) systems. The relatively large velocity offset of the [N\(\text{II}\)] 6583 line from 6100 km s\(^{-1}\) and its large velocity dispersion \((\delta V = 1024 \text{ km s}^{-1})\) may also be attributed to the contamination of the H\(\alpha\) emission of the 6800 km s\(^{-1}\) component. From the line width of the [O\(\text{II}\)] 5007 line and the [O\(\text{III}\)] 3727 line, the 6100 km s\(^{-1}\) component has substantially higher velocity dispersion \((\delta V = 526 \text{ km s}^{-1})\) than the 6800 km s\(^{-1}\) component \((\delta V = 298 \text{ km s}^{-1})\).

M6: located at the intersection between the shock front and a tidal tail of the intruder NGC 7318b. Two velocity systems (6300 and 5700 km s\(^{-1}\)) are detected in the emission lines. The very broad [O\(\text{I}\)] 6300, [N\(\text{II}\)] 6583, and [S\(\text{II}\)] 6731 lines suggest possible blending with lines in another velocity system of \(V \approx 6600 \text{ km s}^{-1}\). The line width of the [O\(\text{III}\)] 5007 line increases, and the very broad velocity dispersion of the 5700 km s\(^{-1}\) component is \(\sim 300 \text{ km s}^{-1}\) (close to the velocity resolution).

4.4. Physical Conditions in the IGM of SQ

5. Physical Conditions in the IGM of SQ

5.1. In the Ionized Gas

5.1.1. IGM Starburst (SQ-A) Region

Four sources (M1, M2, M4, and Nd) in Table 5 are in this region: M1 and M2 are close to the core of the IGM starburst, and M4 and Nd are in the periphery. As indicated in previous H\(\alpha\), CO, and Fabry-Perot observations, there are two velocity systems with recession velocities of ~6600 and ~6000 km s\(^{-1}\), respectively, in this region. The main component of M1 (component 1) and Nd belongs to the 6000 km s\(^{-1}\) system, while the second component of M1 and M2 belongs to the 6600 km s\(^{-1}\) system. M4, with a velocity of ~6200 km s\(^{-1}\), is perhaps associated with the hot X-ray gas (see § 4.3) and has no counterpart in the neutral gas.

We have detected most of the diagnostic lines in both M1 and M2 with relatively high signal-to-noise ratios. Both sources show typical H\(\alpha\) region line ratios. In Table 6 we list the physical parameters derived from the line ratios.

It appears that both cold gas systems, as revealed by the data of M1 and M2, have the metal abundance slightly above the solar value. They both have density less than 100 cm\(^{-3}\) and \(T_{\text{ion}} \sim 40,000 \text{ K}\). These are in the range of typical H\(\alpha\) regions. The ionization parameter of M2 is an order of magnitude lower than that of M1, indicating that the former has a lower density and/or larger distance from the ionizing stars. This is consistent with the more extended morphology and much lower extinction of M2 compared to M1. The extinction derived from the Balmer decrement of M1 is \(A(\text{H}\alpha) = 2 \text{ mag}\), consistent with its rather red continuum color (Sulentic et al. 2001) and the very compact morphology of the 6600 km s\(^{-1}\) H\(\alpha\) gas (Williams et al. 2002).
5.1.2. Shock Front Region

Na, Nb, Nc, and Ne are in the shock front region. They all have \( I(\text{O}^+ \lambda 6300)/I(\text{H} \alpha + [\text{N}^+]) > 0.1 \) and \( I(\text{S}^+ \lambda 6717, 6731)/I(\text{H} \alpha + [\text{N}^+]) > 0.25 \) and therefore are dominantly shock excited (Dopita & Sutherland 1995). The kinematics of the ionized gas in these sources is rather complex but consistent with previous results from the H\( \alpha \) and Fabry-Pérot observations (Sulentic et al. 2001). In Na and Nc, which are north of NGC 7318b, most of the emission lines are dominantly due to the low-velocity (6000 km \( s^{-1} \)) system. Indeed, the H\( \alpha \) observations (Williams et al. 2002) detected only the 6000 km \( s^{-1} \) component in this region. The high-velocity system (6600 km \( s^{-1} \)), with which the low-velocity H\( \alpha \) gas is colliding, shows up only in [O\( \text{i} \) \( \lambda 6300 \) and [O\( \text{iii} \) \( \lambda 5007 \) lines.

The fact that the 6600 km \( s^{-1} \) component is undetected in H\( \alpha \) in the shock front suggests that most of it has been processed by the shock and, consequently, has been converted to hot gas or ionized gas (Sulentic et al. 2001). In the

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**Fig. 8.**—Blue (3700–5400 Å) and red (5600–8000 Å) spectra of four sources along slit M
framework of the models of Dopita & Sutherland (1995), this means that the 6600 km s\(^{-1}\) component does not have the precursor H\(\text{ii}\) region in front of the shock front. This may be one of the reasons why the 6600 km s\(^{-1}\) component is relatively faint in these regions because, without the precursor, its Balmer lines are about a factor of 2.3 fainter (Dopita & Sutherland 1995).

Because of the severe blending among [S\(\text{ii}\)] and [N\(\text{ii}\)] lines, it is difficult to derive the density and other physical parameters using line ratios. Nevertheless, given the close relation between the ionized gas in the shock front and in SQ-A, it is likely that the 6600 and 6000 km s\(^{-1}\) components have the metal abundance of M1 and M2, respectively. From the extended morphology of the H\(\alpha\) emission (Xu et al. 1999) and of the 6000 km s\(^{-1}\) H\(\text{i}\) gas in the shock front, one can safely infer a rather low gas density (much lower than that in M1), possibly in the range of \(n_e \sim 0.01-0.1\) cm\(^{-3}\) as derived by Trinchieri et al. (2003) from the X-ray and H\(\text{i}\) data. For a gas temperature of \(5.8 \times 10^6\) K (Trinchieri et al. 2003) and a head-on collision (\(\phi = 90^\circ\)
| Parameters | Component 1 | Component 2 | M2  | M3  | M4  | Na  | Nb  | Nc  | Nd  | Ne  |
|------------|-------------|-------------|-----|-----|-----|-----|-----|-----|-----|-----|
| $V$ (km s$^{-1}$)........ | 6686         | ...         | 6017| ... | ... | 6197| 5756| 6102| 6693| 6246|
| $\delta V$ (km s$^{-1}$).... | 381          | ...         | 368 | ... | ... | 1010| 1115| 1341| 297 | 499 |
| Flux$^a$................. | 0.94         | ...         | 0.89| ... | ... | 2.05$^b$| 1.40$^b$| 1.68$^b$| 0.18| 0.62 |

| $\text{[S ii]}$ $\lambda$6731 |
|-----------------|--------------|--------------|-----|-----|-----|-----|-----|-----|-----|-----|

| $V$ (km s$^{-1}$)........ | 6700         | 5987         | 6030| ... | ... | 6253| 6164| 5713| 6020| 6697| 6221|
| $\delta V$ (km s$^{-1}$).... | 366          | 346          | 375 | ... | ... | 405 | 611 | 316 | 348 | 619 | 550 |
| Flux$^a$................. | 1.29         | 0.16         | 1.20| ... | ... | 0.11| 1.85$^b$| 0.50$^b$| 0.22$^b$| 0.40| 1.11 |

| $\text{[S ii]}$ $\lambda$6717 |

| $V$ (km s$^{-1}$)........ | 6734         | ...         | 5970| 6471| ... | 5889| 5588| 5927| 6574| 6574| 6251|
| $\delta V$ (km s$^{-1}$).... | 382          | ...         | 429 | 513 | ... | 1024| 1110| 703 | 573 | 515 | 1.18 |
| Flux$^a$................. | 1.63         | ...         | 2.54| 1.14| ... | 8.09$^b$| 4.60$^b$| 3.60$^b$| 0.62| 0.79 |

| $\text{[N ii]}$ $\lambda$6583 |

| $V$ (km s$^{-1}$)........ | 6673         | ...         | 5988| 6445| 6125| 6152| 5722| 6060| 6677| 6249| 6574|
| $\delta V$ (km s$^{-1}$).... | 354          | ...         | 309 | 426 | ... | 618 | 495 | 403 | 430 | 576 | 550 |
| Flux$^a$................. | 0.91         | ...         | 0.58| 0.37| ... | 0.80$^b$| 0.56$^b$| 0.16$^b$| 0.58| 0.41 |

| $\text{[O iii]}$ $\lambda$6300 |

| $V$ (km s$^{-1}$)........ | 6761         | ...         | 5988| 6445| 6152| 6152| 5722| 6060| 6677| 6249| 6574|
| $\delta V$ (km s$^{-1}$).... | 364          | ...         | 357 | 433 | 342 | 495 | 403 | 430 | 576 | 550 | 588 |
| Flux$^a$................. | 10.0         | ...         | 5.64| 1.27| 0.24| 2.79$^b$| 1.48$^b$| 1.78$^b$| 2.87| 3.76 |

| $\text{[O iii]}$ $\lambda$5007 |

| $V$ (km s$^{-1}$)........ | 6889         | ...         | 6001| 6414| 6152| 6152| 5722| 6060| 6677| 6249| 6574|
| $\delta V$ (km s$^{-1}$).... | 354          | ...         | 309 | 426 | ... | 618 | 495 | 403 | 430 | 576 | 550 |
| Flux$^a$................. | 0.91         | ...         | 0.58| 0.37| ... | 0.80$^b$| 0.56$^b$| 0.16$^b$| 0.58| 0.41 |

| $\text{He i} \lambda$5876 |

| $V$ (km s$^{-1}$)........ | 6688         | ...         | 6024| ... | ... | ... | ... | ... | ... | ... | ... |
| $\delta V$ (km s$^{-1}$).... | 383          | ...         | 219 | ... | ... | ... | ... | ... | ... | ... | ... |
| Flux$^a$................. | 0.35         | ...         | 0.19| ... | ... | ... | ... | ... | ... | ... | ... |

| $\text{[O iv]}$ $\lambda$4995 |

| $V$ (km s$^{-1}$)........ | 6530         | 5812         | 5812| ... | ... | 6830| 5512| ... | 6591| ... | ... |
| $\delta V$ (km s$^{-1}$).... | 303          | 269          | 264 | ... | ... | 298 | 206 | ... | 276 | ... | ... |
| Flux$^a$................. | 3.59         | 0.43         | 1.42| ... | ... | 0.31| 0.22 | ... | 0.66 | ... | ... |

| $\text{[N ii]}$ $\lambda$3727 |

| $V$ (km s$^{-1}$)........ | 6655         | ...         | 5986| ... | ... | 5678| 6789| 6233| ... | ... | ... |
| $\delta V$ (km s$^{-1}$).... | 285          | ...         | 342 | ... | ... | 316 | 422 | 339 | ... | ... | ... |
| Flux$^a$................. | 1.45         | ...         | 1.49| ... | ... | 0.37| 0.44 | ... | 0.83 | ... | ... |

| $\text{H} \beta$ |

| $V$ (km s$^{-1}$)........ | 6635         | ...         | 6014| ... | ... | ... | ... | ... | ... | ... | ... |
| $\delta V$ (km s$^{-1}$).... | 279          | ...         | 335 | ... | ... | ... | ... | ... | ... | ... | ... |
| Flux$^a$................. | 0.39         | ...         | 0.67| ... | ... | ... | ... | ... | ... | ... | ... |

| $\text{H} \gamma$ |

| $V$ (km s$^{-1}$)........ | 6600         | 5876         | ... | ... | ... | 6117| 5796| ... | 6600| 6198| ... |
| $\delta V$ (km s$^{-1}$).... | 451          | 355          | ... | ... | ... | 526 | 283 | ... | 937 | 487 | ... |
| Flux$^a$................. | 1.82         | 1.08         | 2.31| 0.82 | ... | 1.48| 2.43 | ... | ... | ... | ... |

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$^a$ Flux of the line emission in $10^{-15}$ ergs s$^{-1}$ cm$^{-2}$.

$^b$ Severely blended.
between the clouds, the shock velocity is $v_{\text{shock}} \sim 460 \text{ km s}^{-1}$ (eq. [1] of Trinchieri et al. 2003). This is very close to the shock velocity derived from the line-of-sight relative velocity (400 km s$^{-1} = 4/3 \times 600/2$ km s$^{-1}$), confirming that the direction of the collision is nearly parallel to the line of sight (Sulentic et al. 2001).

The nondetection of the H$\beta$ emission in Na corresponds to an upper limit of $I(\text{H} \beta) < 0.3 \times 10^{-15}$ ergs s$^{-1}$ cm$^{-2}$. Assuming an intrinsic $I(\text{H} \alpha)/I(\text{H} \beta) = 3$ (Dopita & Sutherland 1995), a very high extinction [$E(\text{H} \beta - \text{H} \alpha) > 1.2$] is hinted at when comparing the H$\beta$ upper limit with the H$\alpha$ flux reported in Table 5. Indeed, substantial IR emission is detected around the Na region (Fig. 2).

Nb and Ne are in the south of NGC 7318b. Nb is very close (within a few arcseconds) to the two “unusual emission-line regions” (U1 and U2) observed by Ohyama et al. (1998). Nb, U1, and U2 all show lines consistent with shock excitation models. However, the velocities of U1 and U2 are 6560 and 6729 km s$^{-1}$, respectively (Ohyama et al. 1998), while the emission lines (except for the [O i] line) in Nb are dominated by the 5700 km s$^{-1}$ component. The spectroscopic observations of Gallagher et al. (2001) for a region
TABLE 6

| Source   | $12 + \log[O/H]$ | $n_{\text{H}}$ | $T_{\text{sh}}$ | $Q$ | $A(H_{\alpha})$ |
|----------|------------------|----------------|-----------------|-----|-----------------|
| M1       | 12 + 0.06        | <100           | ~40000         | ~10^8 | 2.0             |
| M2       | 9.85 + 0.09      | <100           | ~40000         | ~10^7 | 0.64            |

Note.—Col. (1): Source name. Col. (2): Metal abundance derived using the model of Kewley & Dopita (2002), to be compared with the solar value $12 + \log[O/H] = 8.69 \pm 0.05$ (Allende Prieto et al. 2001). Col. (3): Density derived from $[$S$\text{ii}$]/[$S$\text{ii}$] = 6717/6731. Col. (4): Ionization parameter derived, using the model of Evans & Dopita (1985), from two extinction-insensitive line ratios, $[$O$\text{iii}$]/[$H$\beta$] and $[$N$\text{ii}$]/[$H$\alpha$]. Col. (5): Extinction parameter derived, using the model of Evans & Dopita (1985), from two extinction-insensitive line ratios, $[$O$\text{iii}$]/[$H$\alpha$] and $[$N$\text{ii}$]/[$H$\alpha$].

5.3. Dust Emission in the Shock Front Region

The morphological resemblance between the ridge of FIR emission in the residual map (Fig. 3) and the diffuse ridge of radio synchrotron emission (Fig. 4) is striking. Thus, the FIR emission in the shock region might also be associated with the passage of the shock front. If a sufficient fraction of the refractory elements in the colliding clouds are in the solid state, the plasma immediately downstream of the shock will primarily cool by inelastic collisions of electrons and ions on dust grains. Dwek & Werner (1981) showed that for the conditions of the interstellar medium (ISM) in the solar neighborhood, this cooling mechanism dominates over cooling via inelastic collisions between electrons and ions if the gas temperature immediately downstream of the shock exceeds about 10^6 K. For the X-ray ridge in SQ, Trinchieri et al. (2003) found a temperature of 0.5 keV (5.8 \times 10^5 K).

Another necessary condition for the dust emission to dominate the cooling of a shock is that dust grains can survive the sputtering during the cooling. For gas temperatures between 10^6 and 10^7 K, Draine & Salpeter (1979) give the sputtering timescale for a spherical grain of radius $a$ embedded in a plasma of hydrogen density $n_{\text{H}}$ as

$$t_{\text{sput}} \sim 10^6 \left( \frac{a}{\text{m}} \right)^{3} \left( \frac{n_{\text{H}}}{\text{cm}^{-3}} \right)^{-1} \text{yr}.$$  \hspace{1cm} (3)

For $n_{\text{H}} = 0.027 \text{ cm}^{-3}$ (hot gas; Trinchieri et al. 2003) and $a = 0.1 \text{ \mu m}$, $t_{\text{sput}}$ is $3.7 \times 10^4$ yr. This can be compared with the gas cooling timescale $t_{\text{cool}}$ due to collisions with grains.

The cooling mechanism due to dust emission is rather efficient (Dwek & Werner 1981). For sufficiently fast shocks it can tap almost all the kinetic energy flux flowing through the shock, which, following Dopita & Sutherland (1996), is

$$L_T = 2.1 \times 10^{32} \left( \frac{v_{\text{shock}}}{460 \text{ km s}^{-1}} \right)^{3} \left( \frac{n_{\text{H}}}{0.01 \text{ cm}^{-3}} \right) \times \left( \frac{A}{100 \text{ kpc}^{-2}} \right) \text{ ergs s}^{-1} \text{ cm}^{-2},$$ \hspace{1cm} (4)

where $V_{shock}$ and $A$ are the shock speed and the area of the shock front, respectively.
where \( v_{\text{shock}} \) (\( \sim 460 \text{ km s}^{-1} \)) is the shock velocity, \( A \) is the area of the shock, and \( n_0 \) is the upstream number density (for a strong shock, \( n_0 \sim n_\text{H}/4 \)). For the case of the colliding H I clouds in SQ, \( n_0 \) and \( A \) can be estimated to be \( \sim 0.01 \text{ cm}^{-3} \) and \( \sim 100 \text{ kpc}^2 \), respectively. These values are obtained from the typical H I column density of \( 3 \times 10^{20} \text{ cm}^{-2} \) (see Fig. 5 of Sulentic et al. 2001) and by assuming the line-of-sight depth of the shock to be equal to the 10 kpc extent of the radio ridge seen in the plane of the sky.

The resulting value of \( 2.1 \times 10^{42} \text{ ergs s}^{-1} \) for \( L_T \) from equation (4) is to be compared with the observed FIR luminosity of the shock region. In Table 2 this region is bound together with the binary NGC 7318b and NGC 7318a, with a total \( f_{100\mu m} = 76 \text{ mJy} \) and \( f_{100,\mu m} = 230 \text{ mJy} \). The higher resolution 15 and 11.4 \( \mu m \) maps suggest that roughly \( \sim 30\% \) of the FIR emission is due to the shock front; the rest is contributed by the binaries (the two nuclei plus the giant star formation region in the south of NGC 7318b; see Fig. 2).

We calculate the FIR luminosity of the shock region by scaling the predicted form of the spectral energy distribution (SED) (Fig. 11) to a value of 69 mJy at 100 \( \mu m \) (estimated as \( 30\% \) of the flux density of the combined 100 \( \mu m \) emission of 230 mJy from the shock and NGC 7318a/b) and integrating over frequency. Assuming the distance of 80 Mpc, this yields a total dust luminosity \( L_{\text{dust}} = 1.9 \times 10^{42} \text{ ergs s}^{-1} \), comparable to the \( L_T \) of \( 2.1 \times 10^{42} \text{ ergs s}^{-1} \) derived from equation (4). It should also be noted that \( L_{\text{dust}} \) is about an order of magnitude higher than the X-ray luminosity of the ridge, \( L_X \sim 1.5 \times 10^{41} \text{ ergs s}^{-1} \text{ cm}^{-2} \) (Trinchieri et al. 2003), supporting the argument that the dust emission is the dominant cooling mechanism for the shock.

In the cooling timescale of \( 2.1 \times 10^6 \text{ yr} \), the shock will move a distance of 1.0 kpc, or \( 2.7 \) at the distance of SQ. Therefore, the dust emission should trace the shock structure very closely, as predicted by Popescu et al. (2000) for the case of accretion shocks in clusters of galaxies. In the MIR maps (Fig. 2) where the shock front can be discerned from other sources, it is indeed unresolved perpendicular to the axis of the ridge. The predicted SED (Fig. 11) from shock-heated dust has a flux density ratio \( f_{100,\mu m}/f_{60,\mu m} \) of 3.0, very close to the observed color ratio of the combined dust emission of the shock and NGC 7318a/b (Table 2), which is mostly due to photon-heated dust. This highlights the point made by Popescu et al. (2000), in the context of FIR emission from the intracluster medium when viewed from cosmological large distances, that the intergalactic and galactic FIR emission components will be difficult to distinguish on the basis of color, despite the different dust heating mechanisms involved.

We conclude that the observed FIR emission in the shock front region can be accounted for in terms of collisional heating of the grains by the plasma immediately downstream of the shock, provided that the refractory elements in the (preshock) IGM of SQ are mainly in the solid state and the dust abundance in the H I clouds is at least as much as that in the ISM of the Milky Way.

6. SQ-A: STAR FORMATION RATE AND TRIGGERING MECHANISM

6.1. Star Formation Rate

From the H\( \alpha \) luminosity (uncorrected for the extinction) and the 15 \( \mu m \) luminosity of SQ-A, Xu et al. (1999) found that the SFR is \( 0.66 \text{ M}_\odot \text{ yr}^{-1} \) (H\( \alpha \)) or \( 0.81 \text{ M}_\odot \text{ yr}^{-1} \) (15 \( \mu m \)). With the new spectroscopic and FIR data, we can now better constrain these estimates.

First, we exploit the new spectroscopic information to improve the determination of the H\( \alpha \) fluxes using the two narrowband (H\( \alpha \) + [N ii] emission) images: one primarily samples the 6600 km s\(^{-1}\) component and the other the 5700/6000 km s\(^{-1}\) component (Xu et al. 1999). Assuming that the H\( \alpha \)–[N ii] line ratios and the extinction corrections of the 6600 km s\(^{-1}\) component are the same as those of M1 and that those of the 6000 km s\(^{-1}\) component are the same as those of M2, we obtain the H\( \alpha \) fluxes (before and after extinction correction) and the H\( \alpha \) luminosities of the two components in SQ-A (Table 7). The total uncorrected

---

**TABLE 7**

| Velocity Components | \( f_{\text{H} \alpha} \) (10\(^{-14}\) ergs s\(^{-1}\) cm\(^{-2}\)) | Extinction Correction | \( L_{\text{H} \alpha} \) (10\(^{40}\) ergs s\(^{-1}\)) | SFR (M\(_\odot\) yr\(^{-1}\)) |
|---------------------|------------------|----------------------|-----------------|----------------|
| 6600 km s\(^{-1}\) | 8.31 (52.4) | 40.6 | 1.25 |
| 6000 km s\(^{-1}\) | 4.65 (8.38) | 6.43 | 0.20 |
| Total | 13.0 (60.8) | 47.0 | 1.45 |
H\alpha flux, $1.30 \times 10^{-13}$ ergs s$^{-1}$ cm$^{-2}$, is in very good agreement with the result of Xu et al. (1999) of $1.27 \times 10^{-13}$ ergs s$^{-1}$ cm$^{-2}$. The SFR can be derived from the H\alpha luminosities using the STARBURST code (Leitherer et al. 1999) with the following parameters: continuous star formation, Salpeter initial mass function (IMF), $M_{\text{low}} = 1 M_{\odot}$, $M_{\text{up}} = 100 M_{\odot}$, and age of the starburst equal to 10 Myr. The resulting total SFR ($1.45 M_{\odot}$ yr$^{-1}$; see Table 7) is about a factor of 2 higher than that of Xu et al. (1999), primarily because of the extinction correction.

The SFR can also be estimated from the FIR luminosity. The 60 and 100 $\mu$m flux densities of SQ-A (Table 2) correspond to an FIR luminosity of $L_{\text{FIR}(60-100 \mu m)} = 2.52 \times 10^{42}$ ergs s$^{-1}$. In order to obtain the total IR (5–1000 $\mu$m) luminosity, we estimate the total emission of large grains using the median ratio of $L_{\text{IR}}/L_{\text{FIR}(60-100 \mu m)} = 2.06$ found by Popescu & Tuffs (2002) for the cold dust emission in Im-BCD galaxies and approximate the emission of small grains/large molecules by the 15 $\mu$m luminosity ($\nu L_{\nu}$) of SQ-A, which is $1.82 \times 10^{42}$ ergs s$^{-1}$ (Xu et al. 1999). This results in $L_{\text{IR}} = 7.01 \times 10^{42}$ ergs s$^{-1}$. Then assuming that 60% of the bolometric luminosity of the starburst is absorbed by dust and reemitted in the IR (Xu et al. 1994), we obtain a total (bolometric) luminosity of the starburst of $1.17 \times 10^{43}$ ergs s$^{-1}$. Compared to the results of the same STARBURST simulation described above, the FIR luminosity corresponds to an SFR of $0.33 M_{\odot}$ yr$^{-1}$. This is about a factor of 4 lower than the SFR derived from the H\alpha luminosities.

The discrepancy could be caused by the following factors:

1. Possible overcorrection of the H\alpha extinction of the 6600 km s$^{-1}$ component, which is estimated using the Balmer decrement of M1. This could happen if M1, located at the core of the starburst, has encountered more extinction than H\alpha regions elsewhere in SQ-A. However, this seems not to be the case because the Balmer decrement of source Nd, which is at the periphery of the 6600 km s$^{-1}$ H\alpha emission region, gives $A_{\text{H}\alpha} = 1.9$ mag, in good agreement with that of M1 (2.0 mag). Furthermore, even without any extinction correction, the SFR estimated from the H\alpha luminosity is already a factor of 2 higher than that derived from the FIR luminosity. Therefore, the discrepancy is unlikely to be caused by overcorrection of the H\alpha extinction of the 6600 km s$^{-1}$ component.

2. Errors in the $f_{60 \mu m}$ and $f_{100 \mu m}$. A hint for this can be drawn from the relatively low $f_{60 \mu m}/f_{15 \mu m}$ ratio ($=5.5$) of SQ-A, which is about a factor of 4 lower than the mean ($=21.5 \pm 9.4$) of the eight closely interacting and starbursting galaxy pairs observed by Xu et al. (2000). This also explains why the SFR derived using $f_{60 \mu m}$ and $f_{100 \mu m}$ is significantly lower than that derived using $f_{15 \mu m}$ (Xu et al. 1999). Both $f_{60 \mu m}$ and $f_{100 \mu m}$ are derived after the subtraction of brighter sources NGC 7319 and NGC 7320 and so could be seriously affected by errors in the subtraction.

3. A top-heavy IMF. If the starburst has more massive ionizing stars than predicted by a Salpeter IMF, one will have more H\alpha emission for a given bolometric luminosity. There has been evidence that starbursts may tend to have top-heavy IMFs (Rieke et al. 1980; Bernloehr 1993). Given the unusual nature of SQ-A (an IGM starburst triggered by a high-speed collision), it will be very interesting to find out in future studies whether indeed it has an unusual IMF.

Future FIR observations with higher angular resolutions than ISOPHOT (e.g., SIRTF-MIPS observations) will distinguish possibilities 2 and 3.

### 6.2. Triggering Mechanism

Xu et al. (1999) summarized the supporting evidence available by then for the argument that SQ-A is an ongoing starburst. These include (1) strong MIR emission, (2) high H\alpha equivalent line width ($>100$ A), and (3) weak near-infrared (K-band) emission. Dividing the stellar mass estimated from the K-band luminosity by the SFR estimated from the MIR and H\alpha luminosities, Xu et al. (1999) found the age of the starburst to be $<10–20$ Myr. The “$<” sign reflects the possibility that some of the K-band emission is due to an underlying older stellar population (stars stripped from the member galaxies in previous galaxy-galaxy close encounters). New HST observations of Gallagher et al. (2001) indeed found many very young ($\sim 5–6$ Myr) star clusters in the region. Furthermore, a large amount of molecular gas ($5 \times 10^{4}\text{–}10^5 M_{\odot}$) has been discovered in this region (Gao & Xu 2001; Smith & Struck 2001; Lisenfeld et al. 2002), consistent with an ongoing starburst.

Xu et al. (1999) argued that this starburst is triggered directly by the collision between the intragroup cold gas (the 6600 km s$^{-1}$ component of the H\alpha and the cold gas associated with the intruder galaxy NGC 7318b (the 6000 km s$^{-1}$ component of the H\alpha) and is not triggered by any tidal effects between NGC 7318b and other SQ members; thus, it should not be treated as a “tidal dwarf” as suggested by some other authors (e.g., Plana et al. 1999; Mendes de Oliveira et al. 2001). The supporting evidence for this argument includes the following:

1. The H\alpha data show that the star formation in SQ-A is occurring in both the IGM (6600 km s$^{-1}$ component) and the ISM of the intruder (the 6000 km s$^{-1}$ component). In particular, the fact that the H\alpha emission is dominated by the 6600 km s$^{-1}$ component conclusively rules out any interpretation for the starburst that involves only processes within the intruder NGC 7318b.

2. The age of the starburst (10 Myr) is consistent with the dynamical timescale of the high-speed collision. The probability that both the starburst and the collision are happening simultaneously within such a short timescale would be very low if the former is not causally related to the latter.

3. It is even more implausible that, in such a short timescale, two separated tidal dwarf starbursts, one associated with the IGM (the 6600 km s$^{-1}$ component) and the other with the ISM of the intruder (the 6000 km s$^{-1}$ component), are simultaneously happening (within such a small sky region) together with the collision. Therefore, the conclusion is almost inevitable that the three events (the collision and the two velocity components of the starburst) are directly related, as depicted in the collision-induced starburst scenario (as opposed to the tidal dwarf scenario).

Given the high collision velocity ($\sim 600$ km s$^{-1}$) and the apparent link between SQ-A and the shock front in the H\alpha map (Fig. 6), a candidate for the triggering mechanism of the starburst is the star formation induced by a shock, as originally modeled by Elmegreen & Elmegreen (1978). Such a mechanism invokes the gravitational instability in the postshock gas for the triggering of the star formation and has been applied to star formation in the jet-induced...
emission-line regions in the high-z radio galaxy 4C 41.17 by Bicknell et al. (2000). However, in SQ-A, we did not detect a significant component in the Hα emission associated with the postshock gas, which should have redshift \( \sim 6300\ km\ s^{-1} \) (assuming that H i clouds in the 6000 and 6600 km s\(^{-1}\) systems have similar mass distributions). Instead, given that the two Hα components are closely associated with the two H i velocity systems detected in this region (Williams et al. 2002), the star formation is apparently happening in the pre-shock gas (see § 7.1 for arguments on why 6000 km s\(^{-1}\) gas is not postshock gas).

A better model can be drawn from the theory developed by Jog & Solomon (1992, hereafter JS), initially aimed to explain the origin of the intense starbursts seen in colliding, gas-rich, field spiral galaxies. In that theory, it is assumed that the collisions between the H i clouds, which have much larger filling factors than the molecular clouds, of two colliding gas systems lead to the formation of a hot (\( \sim 1\ keV \)) ionized, high-pressure remnant gas. The overpressure due to this hot gas causes a radiative shock compression of the outer layers of preexisting giant molecular clouds (GMCs), which are embedded in the H i clouds before the collision. The “squeezing” radiative shock lasts only about \( 10^4\ yr \) (the crossing time of individual H i clouds), too short to destroy a GMC but long enough to trigger instabilities in the thin outer layers. These layers become gravitationally unstable and a burst of massive star formation is ignited in the initially barely stable GMCs.

It is interesting to note that Xu et al. (1999) discounted this theory for the following considerations: (1) it was not clear whether there is any molecular gas in the SQ-A region because it is very rare for molecular gas to be seen so far away (\( \geq 20\ kpc \)) from galaxy centers; and (2) according to Pietsch et al. (1997), SQ-A was in an X-ray hole in the ROSAT map, and hence the signal for the hot remnant gas produced by the ongoing collision between H i clouds was missing. Since the publication of Xu et al. (1999), several new observations have shed new light on above issues and lent support for the JS model. First of all, Gao & Xu (2000) made the first detection of molecular gas in SQ-A with high angular resolution (\( \sim 8'' \)) interferometric CO observations using BIMA. This was later confirmed by single-dish observations of Smith & Struck (2001) and Lisenfeld et al. (2002). The mass of the detected molecular gas is \( \sim 10^5\ M_\odot \), and both velocity components (6600 and 6000 km s\(^{-1}\)) were detected. Secondly, the new Chandra X-ray image of Trinhchieri et al. (2003), which is much more sensitive than the ROSAT maps, shows that there is indeed an X-ray source at the position of the core of SQ-A (corresponding to the peak in the Hα map of the 6600 km s\(^{-1}\) component and the peak in the radio continuum maps).

Indeed, it is expected in the scenario depicted by the JS model that the starburst should have two components with the same velocities as the colliding cold gas systems since the motions of the preexisting GMCs (within which the starburst is taking place) are little affected by the collision. This is because (1) the GMCs do not collide with each other as a result of very low filling factors (JS) and (2) given GMCs’ very high density and compact configuration and the rather short timescale (\( \sim 10^7\ yr \)) for collisions between individual H i clouds (within which the GMCs are embedded), little momentum will be transferred from the GMCs to surrounding low-density gas during the collision. The compression radiative shock by the remnant gas is symmetric and hence will not affect the momentum of the GMCs.

In this scenario, the starburst starts immediately after the collision taking place. Following JS (see their eq. [17]), the SFR can be estimated as

\[
\text{SFR} = 1\ M_\odot\ yr^{-1}\left(\frac{M_{\text{mol}}}{10^5\ M_\odot}\right)\left(\frac{f}{0.2}\right)\left(\frac{\alpha_m}{0.1}\right)\left(\frac{\text{SFE}}{0.5}\right) 
\times \left(\frac{t}{10^7\ yr}\right),
\]

(5)

where \( M_{\text{mol}} \sim 10^5\ M_\odot \) is the total molecular gas in this region and \( f \sim 0.2 \) is the fraction of this gas that is participating in the collision. It is conceivable that a large fraction of the two gas systems may miss the collision if they both are in armlike configurations (when the collision is not perfect). Moreover, \( \alpha \) is another fraction, defined by the mean ratio of the mass of the unstable layer to the total mass of a GMC that is participating in the collision. JS found that typically \( \alpha_m = 0.1 \). Following again JS, we assume that the typical star formation efficiency (SFE) for the unstable GMC layer is SFE = 0.5. The time for the two gaseous systems to pass each other is \( t \sim 10^7\ yr \). With these plausible parameters, the SFR derived in equation (5) agrees very well with what is observed for SQ-A (Table 7).

In principle, the triggering mechanism proposed for the starburst in SQ-A should also work in other regions in SQ where the large-scale collision is taking place. The condition is the availability of preexisting GMCs. Indeed, in the south of NGC 7318b (around the position of R.A. = \( 22^h35^m59^s \), decl. = \( 33^\circ57^\prime30^\prime \) [J2000.0]), where marginally significant evidence for the CO emission could be found in the BIMA image (Gao & Xu 2000), young star clusters (10\(^7\) yr; Gallagher et al. 2001) and the Hα emission (Xu et al. 1999) indicate current star formation. This region was detected with bright X-ray emission (Pietsch et al. 1997; Sulentic et al. 2001; Trinhchieri et al. 2003), and the long slit spectroscopic observations of Gallagher et al. (2001) show both the 5700 and 6600 km s\(^{-1}\) systems. These are consistent with the fact that the star formation in this region may also be triggered by the same mechanism as modeled by JS. Gao & Xu (2000) did not detect any CO emission in the shock front. This may explain why there is no conspicuous star formation, either in the form of young clusters (Gallagher et al. 2001) or as bright point sources in Hα images (Xu et al. 1999), in this region. It should be noted that Lisenfeld et al. (2002) reported detection of the CO emission in the shock front region. However, given the large beam (22") of their single-dish observations, it is not very certain that the emission is really from the shock front.

7. DISCUSSION

7.1. Is the 6000 km s\(^{-1}\) Component the Postshock Gas?

In this paper we have accepted the suggestion of Moles et al. (1997) that both the 5700 and 6000 km s\(^{-1}\) H i gas components belong to NGC 7318b, the velocity difference being due to the rotation. Williams et al. (2002) questioned such a scenario based on the apparent separation between the two H i components, in both spatial and velocity distributions. Sulentic et al. (2001) disputed this argument and further supported the suggestion of Moles et al. (1997). They pointed out the connection of the two H i components...
through the ionized gas in the shock front. In addition, the Fabry-Pérot observations (Sulentic et al. 2001) demonstrate that the velocity of the emission-line regions along an arc, which includes the shock front and links both the 5700 and 6000 km s$^{-1}$ $\text{H} \ \text{i}$ components, changes continuously from $\sim$5700 to $\sim$6000 km s$^{-1}$, indicating a kinematic connection between the two velocity systems.

An alternative picture, as suggested by Lisenfeld et al. (2002), is that the 6000 km s$^{-1}$ gas is indeed linked to the 5700 km s$^{-1}$ component, but the velocity difference is due to the current interaction with the 6600 km s$^{-1}$ component, instead of the internal rotation of the ISM of NGC 7318b. Since the timescale is too short for any gravitational effects, the only way to accelerate the 5700 km s$^{-1}$ gas to 6000 km s$^{-1}$ during the current collision is through the shock. Hence, in such a scenario, the 6000 km s$^{-1}$ component should be the postshock gas. However, our spectroscopic observations do not support this hypothesis. In both the SQ-A region and the shock front region, where there was no detection of the 5700 km s$^{-1}$ $\text{H} \ \text{i}$ gas, there is no evidence for a 5700 km s$^{-1}$ component in the ionized gas, either. If all the 6000 km s$^{-1}$ cold gas ($\text{H} \ \text{i}$, molecular, and the ionized) were processed gas already passed through the shock front, then there would be nothing left for the 6600 km s$^{-1}$ gas to collide with. Our conclusion is that the 6000 km s$^{-1}$ component is not the postshock gas.

7.2. Distribution of Preshock Gas

Nevertheless, the 5700 and 6000 km s$^{-1}$ components of the $\text{H} \ \text{i}$ gas do show peculiarities: (1) they are outside the main body of NGC 7318b; (2) their maps do not show a rotating disk morphology, even after adding the ionized gas in the shock front; (3) in particular, the 6000 km s$^{-1}$ component appears to be a round, extended cloud centered at SQ-A (Fig. 9 of Williams et al. 2002), with little sign of any substructure.

Moles et al. (1997) and Sulentic et al. (2001) argued that NGC 7318b had been a “normal” gas-rich galaxy before it entered SQ. In this scenario, it is difficult to explain the above peculiarities of the $\text{H} \ \text{i}$ gas that is presumably associated with the galaxy. There are also “abnormal” features in its optical morphology: (1) its outer optical disk is one-side loped toward the north; and (2) it has several long, open arms that are usually seen in interacting galaxies (the so-called tidal tails). Williams et al. (2002) argued that NGC 7318b is perhaps not entering the SQ the first time. However, its relative velocity is too high for it to be gravitationally bound to the SQ system; therefore, repeat passages seem to be unlikely.

Another possibility is that these abnormal features are due to interaction with the elliptical galaxy NGC 7318a, which has to be at least $\sim$100 kpc behind NGC 7318b at the moment, although the projected distance is only $\sim$10 kpc. The requirement on the large line-of-sight distance between NGC 7318a and NGC 7318b is because the timescale for tidal effects is a few times $10^2$ Myr. Within this time, with the projected relative velocity ($\delta V \approx 900$ km s$^{-1}$), NGC 7318b would have moved a few times $10^2$ kpc away from NGC 7318a since the close encounter. This also requires that NGC 7318b move almost along the line of the sight; otherwise, the projected distance between NGC 7318a and NGC 7318b would be much larger. Indeed, from the narrow width of the shock front and the fact that in the shock front and in SQ-A emission-line systems with velocities of $\sim$6600 and $\sim$6000 km s$^{-1}$ are found on top of each other, Sulentic et al. (2001) argued that the direction of the relative velocity of NGC 7318b must be close to the line of sight. Future works such as higher sensitivity and higher resolution H $\text{i}$ maps and detailed theoretical simulations will help to solve the puzzle related to the $\text{H} \ \text{i}$ and optical morphology of NGC 7318b.

As shown by Sulentic et al. (2001), the preshock 6600 km s$^{-1}$ cold gas is in a huge arc (longer than 100 kpc), with the SQ-A in the northwest tip. This gaseous arc is likely to be a tidal feature related to a previous close encounter between member galaxies, which could have happened a few times $10^2$ Myr ago (Moles et al. 1997; Sulentic et al. 2001). The concentration of the $\text{H} \ \text{i}$ gas (Williams et al. 2002) and the molecular gas (Gao & Xu 2000) in SQ-A, which is more than 20 kpc away from any galaxy center, may indeed have the same origin as those $\text{H} \ \text{i}$ knots observed along the tidal tails (particularly at tips of tidal tails) of interacting galaxies (Hibbard & von Gorkom 1996; Duc et al. 2000; Braine et al. 2001), although the triggering mechanism of the IGM starburst is different from those of star-forming tidal dwarfs as modeled by Barnes & Hernquist (1992) and Elmegreen, Kaufman, & Thomasson (1993).

8. Conclusions

The compact galaxy group Stephan’s Quintet (SQ) provides a unique target in the local universe for studying the effects of high-velocity collisions ($\sim$1000 km s$^{-1}$) between two systems rich in cold gas. The two phenomenal events currently taking place in the IGM of SQ, namely, the large-scale shock ($\sim$40 kpc) and the IGM starburst SQ-A ($\text{SFR} = 1.45 \ M_\odot \text{yr}^{-1}$), are very likely to be triggered by the same ongoing collision between the intruder galaxy NGC 7318b ($v = 5700$ km s$^{-1}$) and the IGM ($v = 6600$ km s$^{-1}$). In this paper we provided new constraints on the physical conditions in the IGM involved and investigated the physical mechanism linking these events with the collision using new FIR images at 60 and 100 $\mu$m (ISOPHOT C100 camera), radio continuum images at 1.4 GHz (VLA B configuration) and 4.86 GHz (VLA C configuration), and long-slit optical spectrographs (Palomar 200$''$ telescope).

We found that the shock front, which appears as a radio ridge and dominates the radio continuum emission of SQ, has a steep nonthermal spectral index ($\alpha = 0.93 \pm 0.13$). Its FIR-to-radio flux ratio is extremely low ($q < 0.59$) compared to that of galaxies ($q = 2.3 \pm 0.2$), consistent with the hypotheses that the relativistic electrons responsible for the radio emission are accelerated by the large-scale shock (in contrast to the relativistic electrons in galaxy disks that are likely to be accelerated by supernova remnants). Its observed IR emission can be explained in terms of collisional heating of dust grains by the plasma immediately downstream of the shock. The long-slit spectra of sources in this region have typical emission-line ratios of shock-excited gas. The very broad line widths ($\text{FWHM} \geq 1000$ km s$^{-1}$), as well as the fact that in some cases more than two velocity systems were detected along the same line of sight, provide further evidence for an ongoing collision in this region. The magnetic field strength estimated using the minimum-energy assumption is $\approx 10 \mu\text{G}$. The implied energy density of the electromagnetic field is significantly lower than the IGM thermal energy density derived from the X-ray emission.
indicating a minor role played by the electromagnetic force on the dynamics in the shock front. No linearly polarized emission brighter than 50 μJy beam$^{-1}$ was found in any component of SQ at either 1.40 or 4.86 GHz, indicating that the magnetic fields may be disordered, and both “beam depolarization” and Faraday rotation may have caused the reduced polarization.

The IGM starburst SQ-A was clearly detected in both the FIR and radio bands. Its radio spectral index ($\alpha = 0.8 \pm 0.3$) and the FIR-to-radio ratio ($q = 2.0 \pm 0.4$) are consistent with those of star formation regions. The optical spectra of two sources in this region, M1 ($v = 6600$ km s$^{-1}$) and M2 ($v = 6000$ km s$^{-1}$), have typical line ratios of Hβ regions. The metallicity of M1 is $12 + \log(O/H) = 8.76 \pm 0.06$ and that of M2 is $12 + \log(O/H) = 8.95 \pm 0.09$, both being slightly higher than the solar value ($12 + \log(O/H) = 8.69 \pm 0.05$; Allende Prieto et al. 2001). This result confirms that the IGM is stripped gas from galaxies and rules out the possibility that it is primordial. According to the Balmer decrement of M1, the 6600 km s$^{-1}$ component of the IGM starburst is heavily obscured ($A_b = 2.0$), while the Balmer decrement of M2 indicates a moderate extinction ($A_b = 0.64$) for the 6000 km s$^{-1}$ component. The SFR estimated from the extinction-corrected Hα luminosity of SQ-A is $1.45 M_\odot$ yr$^{-1}$, of which 1.25 $M_\odot$ yr$^{-1}$ is due to the 6600 km s$^{-1}$ component and 0.20 $M_\odot$ yr$^{-1}$ is due to the 6000 km s$^{-1}$ component. The SFR estimated using the FIR luminosity is significantly lower (SFR = 0.33 $M_\odot$). The discrepancy is due to either errors in the FIR flux densities or a top-heavy IMF. The very good agreement in velocity between Hα and Hγ (Williams et al. 2002) for both components suggests strongly that the starburst is occurring in the preshock gas rather than in the postshock gas. A model (JS) based on a scenario in which a starburst is triggered in the outer layers of preexisting (preshock) GMCs compressed by surrounding shocked gas (which is the Hγ gas before the collision) can be applied to SQ-A and explain the observed SFR, the two components of the starburst, and the apparent link between SQ-A and the large-scale shock front.

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ERRATUM: “PHYSICAL CONDITIONS AND STAR FORMATION ACTIVITY IN THE INTRAGROUP MEDIUM OF STEPHAN’S QUINTET” (ApJ, 595, 665 [2003])

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In § 4.1, when describing the optical long-slit observations, there was a mistake in the reported position of slit N, due to a typo. The central position of slit N should be 22h35m59.6s +33°58′00″ (J2000.0), instead of 22h35m59.8s +33°58′00″ (J2000.0). This also affects the positions of the spectroscopic sources along slit N given in Table 4 (together with sources along slit M). Here we give a new Table 4 with the mistakes corrected.

| Source ID | R.A. (J2000.0) | Decl. (J2000.0) | Aperture (arcsec) |
|-----------|----------------|----------------|------------------|
| M1        | 22 35 59.18    | 33 58 45.3     | 9 × 2            |
| M2        | 22 35 58.11    | 33 58 55.6     | 15 × 2           |
| M3        | 22 36 01.90    | 33 58 18.8     | 18 × 2           |
| M4        | 22 35 56.54    | 33 59 10.9     | 8 × 2            |
| Na        | 22 35 59.57    | 33 58 01.8     | 14 × 2           |
| Nh        | 22 35 59.71    | 33 57 36.8     | 8 × 2            |
| Ne        | 22 35 59.42    | 33 58 26.2     | 8 × 2            |
| Nd        | 22 35 59.30    | 33 58 47.9     | 8 × 2            |
| Ne        | 22 35 59.82    | 33 57 17.4     | 15 × 2           |

Note—This corrected table shifts the positions of the sources along slit N by 2′5 to the west. It does not impact the main conclusions of the paper at all. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.