Hot Interstellar Gas in the Irregular Galaxy NGC 4449

Dominik J. Bomans\textsuperscript{2} and You-Hua Chu

\textit{Astronomy Department, University of Illinois, 1002 W. Green St., Urbana, IL 61801, USA}

and

Ulrich Hopp\textsuperscript{2}

\textit{Universitätssternwarte München, Scheiner Str. 1, 81679 München, Germany}

\textbf{ABSTRACT}

NGC 4449 is an irregular galaxy with a moderately high star formation activity. The massive stars in NGC 4449 have given rise to many bright HII regions, superbubbles, supergiant shells, and “chimney-like” radial filaments. ROSAT X-ray observations of NGC 4449 have revealed four point-like sources and a wide-spread diffuse emission. The spectral properties of the diffuse component suggest that the emission originates from hot interstellar gas. We have compared deep ground-based Hα images with the X-ray images of NGC 4449 to determine the relationship between the hot (10^6 K) and the warm (10^4 K) components of the interstellar gas. We have also used an archival Hubble Space Telescope WFPC2 image of NGC 4449 taken through the F606W filter to examine the massive stellar content of the X-ray-emission regions. We find that hot interstellar gas exists in (1) active star forming regions, including the giant HII region CM16, (2) probable outflows from star forming regions, and (3) the supergiant shell SGS2. The X-ray data have been used to derive the rms electron density, mass, and thermal energy of the hot interior of SGS2. Finally we discuss the origin of SGS2 and implications of the detection of diffuse X-rays in irregular galaxies.

\textit{Subject headings:} Galaxies: Irregular — Galaxies: NGC 4449 — Galaxies: ISM — X-rays: Galaxies

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\textsuperscript{2}Feodor Lynen Fellow of the Alexander von Humboldt-Foundation

\textsuperscript{3}Visiting Astronomer, Calar Alto Observatory
1. Introduction

Diffuse X-ray emission has been detected in late-type galaxies, indicating the existence of hot \((10^6 \text{ K})\) interstellar gas (e.g., M33 – Snowden & Pietsch 1997). The hot interstellar gas can be studied with particularly high spatial resolution in the Large and Small Magellanic Clouds (LMC and SMC), as these are the two nearest neighboring galaxies. The ROSAT observations of the LMC has shown unprecedented details of the bright diffuse X-ray emission associated with the giant HII region 30 Doradus complex, large shell structures, as well as regions with no obvious ionized interstellar structures (Snowden & Petre 1994, Chu 1990, Bomans et al. 1997). The SMC, on the other hand, shows very little diffuse X-ray emission (Snowden 1990).

What determines the level of diffuse X-ray emission, or the amount of hot interstellar gas? Is the bright diffuse emission of the LMC or the lack of diffuse emission in the SMC the norm for irregular galaxies? To answer these questions, other irregular galaxies need to be studied in detail. We have chosen the irregular galaxy NGC 4449, which is similar to the LMC in size and mass (Bajaja et al. 1994) and has been relatively well-studied in many wavelengths.

As a probable member of the Canis Venaticorum galaxy group, NGC 4449 is at a distance of 3 Mpc (Tully 1988) or 5.4 Mpc (Schmidt & Boller 1992); we adopt the latter. The inclination of NGC 4449 determined from isophote analysis of the continuum light is \(\sim 43^\circ\) (Tully 1988). NGC 4449 is one of the first galaxies in which diffuse ionized filaments were detected (Sabadin & Bianchini 1979). Its moderately high star formation activity apparently has produced long filaments and a frothy structure of the warm \((10^4 \text{ K})\) ionized interstellar medium (Hunter & Gallagher 1992). The HI halo, extending over more than 1', is detected around NGC 4449 (van Woerden et al. 1973, Bajaja et al. 1994). Recently, Klein et al. (1996) detected a large synchrotron emission halo around NGC 4449, and speculated the existence of a hot gaseous halo. They also found an ordered magnetic field on kpc scales, the first detection in an irregular galaxy other than the LMC. A super-luminous supernova remnant (SNR) in NGC 4449 has been detected in both radio continuum (Seaquist & Bignell 1978) and X-ray (Blair et al. 1983).

X-ray point sources in NGC 4449 have been detected by Einstein observations; however, the diffuse emission in NGC 4449 is not obvious until ROSAT observations become available. In this paper we report our analysis of X-ray and optical observations of the interstellar medium in NGC 4449. The observations and data reduction are described in §2. We discuss the large interstellar shell structures and filaments of NGC 4449 in §3. The nature of the X-ray sources and the relationship between the hot and warm interstellar gases are analyzed in §4. Finally, in §5 we discuss the relationship between the \(10^6 \text{ K}\) hot gas and massive stars, examine the hot interior of the supergiant shell SGS2, and discuss the origin of SGS2 and implications of the detection of diffuse X-rays in irregular galaxies.

2. Observations and Reductions

2.1. Optical Observations

To examine the warm ionized interstellar gas, two sets of optical emission-line and continuum images were obtained. The primary set of images, having a large field of view and high sensitivity but taken under non-photometric conditions, are used to examine the global structure. The secondary set of images, having a smaller field of view but multiple wavelength coverage, are used to flux-calibrate the primary data and to investigate the ionization and excitation condition of the HII gas.

The primary set of images of NGC 4449 were obtained with the Calar Alto Observatory 3.5m telescope in January 1991. The prime focus focal reducer was used, giving an effective focal ratio of 1:2.7. The detector was a GEC 1152 – Snowden & Pietsch 1995). The hot interstellar gas (e.g., M33 \(\sim 10^5 \text{ K}\) hot gas and mas-
ments to optimize the subtraction. The point spread functions (PSFs) of the on- and off-line images were so different that relatively large residuals remained after the subtraction. We therefore convolved both frames with narrow Gaussian filters to minimize the differences in the PSF, withstanding a small trade-off in resolution. Continuum subtraction using these differences in the PSF, withstanding a small trade-off in resolution. Continuum subtraction using these differences in the PSF, withstanding a small trade-off in resolution. Continuum subtraction using these differences in the PSF, withstanding a small trade-off in resolution. We therefore convolved both frames with narrow Gaussian filters to minimize the differences in the PSF, withstanding a small trade-off in resolution. We therefore convolved both frames with narrow Gaussian filters to minimize the differences in the PSF, withstanding a small trade-off in resolution. We therefore convolved both frames with narrow Gaussian filters to minimize the differences in the PSF, withstanding a small trade-off in resolution. We therefore convolved both frames with narrow Gaussian filters to minimize the differences in the PSF, withstanding a small trade-off in resolution.

The continuum image of NGC 4449 is shown in Fig. 3. In Fig. 2 the central portion of the continuum-subtracted Hα image is overlaid with sketches of the principal filamentary nebular features and reference numbers to ease later discussions. Positions and remarks of these features are tabulated in the Appendix, Table A1 for shells and Table ?? for irregular filaments. The faint emission blob marked with “ghost” in Fig. 2 is an internal reflection of the neighboring bright stars produced in the optical path of the instrument.

The secondary data set of NGC 4449 was obtained with the Calar Alto 3.5m telescope in March 1988 using the normal prime focus CCD camera equipped with a 580×380 GEC chip. The field of view was 4′×3′. Observations were made through filters centered at Hα, Hβ, [OIII], red continuum at 870 nm, and Johnson V, respectively. The seeing was 2″, but the sky was photometric. Planetary nebulae from the list of Kaler (Kaler 1976, Kaler 1983) were observed as emission line standards.

The flux-calibrated secondary images provide an independent flux calibration for our primary Hα image. We use a small, reasonably isolated H II region at 12h28m08s, +44°06′25″ (J2000) for the flux transformation. Using the filter curves and an [NII]λ6583/Hα ratio of 0.15 for the ionized gas in NGC 4449 (Lequeux et al. 1979), we estimate the contribution of the [NII] line to the primary image to be 10%. The resultant limiting surface brightness of our primary Hα image is 9.0 × 10⁻¹⁸ erg cm⁻² s⁻¹ arcsec⁻², corresponding to a limiting emission measure of 4.5 cm⁻⁶ pc if the electron temperature is 10⁸ K. This limiting emission measure could be still lower for the diffuse ionized gas, since the [NII] lines can be enhanced in the case of dilution of the ionizing photon field (e.g. Domgørgen & Mathis 1994).

2.2. X-ray Observations

NGC 4449 has been observed by the Einstein Observatory with an Imaging Proportional Counter (IPC; I2123, 1.7 ks) and a High Resolution Imager (EHRI; H4967, 32.4 ks), and the Röntgensatellit (ROSAT) with a Position Sensitive Proportional Counter (PSPC; RP600137, 7.85 ks) and a High Resolution Imager (RHRI: WH600743, 20.1 ks; WH600865, 41.3 ks). The ROSAT PSPC observation, having the highest sensitivity, is used to extract spectral information and to analyze diffuse emission. Both EHRI and RHRI observations are used to distinguish point sources from the diffuse emission.

The X-ray observations of NGC 4449 were retrieved from the High Energy Astrophysics Science Archive Research Center (HEASARC) at Goddard Space Flight Center of NASA. The software packages of IRAF/PROS were used for the data analysis. The PSPC image of NGC 4449 in the 0.1–2.4 keV band smoothed with a Gaussian of σ=10″ is displayed in Fig. 3a; the RHRI image WH600743 smoothed with a Gaussian of σ=3″ is displayed in Fig. 3b.

The X-ray images of NGC 4449 show point sources as well as diffuse emission. The X-ray emission in the PSPC image can be divided into seven discrete regions. These regions are marked in Fig. 3. The EHRI and RHRI images of NGC 4449 show that regions 1, 2, and 3 are dominated by bright point sources, and region 5 contains a weaker point source superimposed on diffuse emission. Note that the diffuse emission in the northern part of NGC 4449, centered on region 6, is detected even in the RHRI image.

To align the X-ray and optical images of NGC 4449, we use the super-luminous SNR whose position is well determined from radio and optical observations (Seaquist & Bignell 1978). This SNR corresponds to our X-ray source 2 in Fig. 3, and its optical counterpart is marked in Fig. 3. The alignment between the X-ray and optical images should be accurate to

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about $2''$. In Fig. 6a we show a grey-scale Hα image of NGC 4449 overlaid by X-ray contours derived from the PSPC data, while Fig. 6b overlayed by X-ray contours from the HRI data.

We have extracted background-subtracted spectra for the seven regions marked in Fig. 5 and a region (No. 8) that includes the entire galaxy. The background is scaled from regions located outside but close to the galaxy. Two different background regions have been used, but the resultant spectra and fluxes are virtually identical within error limits. For sources with sufficient counts, we have fitted the spectra using the Raymond & Smith (1977) thin plasma emission model with a 30% solar abundance, as measured from H II regions in NGC 4449 (Lequeux et al. 1979). For sources with insufficient counts (<150 counts) for spectral fits, we adopt the absorption column density determined from the spectral fits of the brightest sources, and estimate plasma temperatures based on the spectral shape. We compare the spectral shape to those of other plasma emission sources, such as giant H II regions in M101 (Williams & Chu 1995) and superbubbles and supergiant shells in the LMC (Chu et al. 1993; Bomans et al. 1994), and adopt the corresponding plasma temperatures. The number of source counts, foreground absorption column densities, plasma temperatures, and X-ray luminosities in the 0.1–2.4 keV and 0.5–2.4 keV bands of the seven regions and of the whole galaxy are tabulated in Table 1.

For a quantitative analysis of the spectral properties of the apparent diffuse emission a subtraction of the three point source would be extremely useful. We did not apply this step for the following reasons: first, the point-sources are relatively close to each other and no isolated bright point-source is available as a template, therefore the exact subtraction of the wings of the point-spread function is very uncertain. Secondly, this exact subtraction is critical since the underlying possible diffuse emission in the area of the galaxy bar is faint. We used instead images in selected energy bands to investigate the large scale distribution of the diffuse emission in NGC 4449 (see section 4.2). Observations with the forthcoming X-ray satellites will provide the needed spatial and spectral resolutions.

3. Large Interstellar Shells and Filaments in NGC 4449

Star formation is quite active in NGC 4449. Nearly the entire optical extent of the galaxy is covered with H II regions and prominent filamentary structures. The two most luminous H II regions, CM16 and CM39 (Crill & Monnet 1969), rival the archetypical giant H II region 30Dor in both size and luminosity. The filamentary structures have been previously detected and discussed by HG90, HG92, Bomans & Hopp (1993), and Hill et al. (1994). We have identified the most prominent filaments and marked them in Fig. 3. Some of the filaments form large shell structures, such as supergiant shells and superbubbles (listed in Table A1), some filaments extend radially, while others are irregular or multiple (listed in Table ??). Many filaments may be physically associated with large star formation regions. For example, the giant H II region CM16 appears to be connected with the superbubbles SB3 and SB4 and the filaments FIL27–29 and perhaps FIL6 and FIL30, forming a complex structure covering 1 kpc. Below we discuss supergiant shells, superbubbles, and other filaments separately.

We have identified five supergiant shells with diameter greater than 500 pc, SGS1–5. SGS1 was previously identified by HG90. SGS2 corresponds to HG92’s filaments 5 and 6. SGS3–5 have not been previously documented. Note that our division between supergiant shells and superbubbles may not be physical. The largest superbubbles have sizes approaching the 500 pc threshold for supergiant shells. Furthermore, if NGC 4449 is at a smaller distance (3 Mpc, Tully 1988), then SGS1 and SGS3 will not be qualified as supergiant shells.

The five supergiant shells have very different physical properties. See Fig. 8 for the outlines of these supergiant shells. SGS1 is adjacent to the giant H II region CM16, reminiscent of the supergiant shell LMC2 to the giant H II region 30Dor in the LMC. It contains a luminous OB association. SGS2 consists of a set of very long (> 1 kpc) curved filaments west of the ridge of intense star formation. The mid section of SGS2 lies at distances up to 2 kpc from the star formation regions. SGS2 is the largest known ionized supergiant shell. SGS3, like SGS1, encompasses a luminous OB association; however, unlike the other supergiant shells, SGS3 is isolated at 3 kpc away from the high surface brightness bar of the galaxy. SGS4...
is faint, with no apparent concentration of luminous associations. SGS5 is faint and is superimposed on a complex background; its identification may be uncertain.

We use “superbubbles” to refer to large shells with diameters <500 pc. We have identified nine superbubbles, SB1–9. Three superbubbles, SB3, SB4 and SB5, appear to be “blisters” extending from giant H II regions. The others are associated with OB associations, similar to the common superbubbles in the LMC, such as N44 (Oey & Massey 1995; Will et al. 1997).

The non-shell type filamentary structures we cataloged are by no means complete, because crowding in the main body of the galaxy prohibits reliable identifications of nebular structures. Some of the filaments have been previously identified by HG90; these are noted in Table ???. Among these non-shell type filaments, the most remarkable ones are those oriented perpendicular to the major axis of NGC 4449 – FIL3, 15, 16, 19, 22, 23, 24, 25, 26, 27, 28, 29, and 37. These filaments are reminiscent of the chimneys in edge-on galaxies such as NGC891 (Dettmar 1990; Rand et al. 1990) and possibly the HI worms in our galaxy (Heiles 1984). Interestingly, the distribution of filaments in NGC 4449 is far from uniform; the western side of the galaxy is populated by numerous radial filaments, while the eastern side has fewer filaments and the filaments are tangential to the major axis of the galaxy. This distribution suggests that energy and gas outflows into the halo take place preferentially on the western side of the galaxy. This will be discussed further in §5. The interpretation of radial filaments as chimneys is based on our understanding of dwarf irregular galaxies (see e.g. Skillman 1994) that NGC 4449 is a flattened body with a large scale height for its neutral gas.

Finally, we note that the [O III]/Hα ratios of the brightest filaments (e.g., FIL2 and FIL3) are lower than those of their adjacent H II regions, regardless of their distance from the H II regions. Similar behavior of the [O III]/Hα ratio has been observed in SGSs and filaments in the LMC (Hunter et al. 1994). This seems to indicate that the filaments are not photoionized in the same way as the classical HII regions by UV radiation of O stars. Other considerations need to be taken into account, such as dilution of the photon-field (Domgörgen & Mathis 1994), an intrinsically very soft ionizing photon field (e.g., Skillman et al. 1997), turbulent mixing layers (Slavin et al. 1993), or ionization by soft X-rays from cooling hot gas.

4. Hot Gas in NGC 4449

Hot (10⁶ K) interstellar gas is best studied in X-rays. However, stellar coronal emission and X-ray binaries contribute to the X-ray flux observed. Thus we need to consider carefully the nature of the X-ray sources before we use the X-ray emission to extract information on the hot interstellar gas. Note that individual SNRs in NGC 4449, if detected, would appear as point sources.

4.1. Physical Nature of the X-ray Sources

Seven discrete regions of X-ray emission are identified in NGC 4449 (Fig. 3); some are dominated by point sources while others by diffuse emission (Figs. 3a, b). Note that at the distance of NGC 4449 (~5.4 Mpc), a “point source” could be as extended as 157 pc for the RHRI, and 780 pc for the PSPC. Since X-ray point sources and diffuse sources often have very different spectral characteristics (Williams & Chu 1995), we may use the X-ray spectral properties and surface brightness to diagnose the nature of a source. We have extracted X-ray spectra from the PSPC data for these seven regions and for the entire galaxy. These spectra are displayed in Figs. 6a-h. We have also used Raymond & Smith’s (1977) plasma emission models and Morrison & McCammon’s (1983) absorption characteristics to make spectral fits in order to derive X-ray luminosities. For sources with insufficient counts for a spectral fit, we estimate the X-ray luminosity by adopting the Galactic HI column density log N_H = 20.2 (Fabbiano 1988) for the absorption column and adopting plasma temperatures of well-observed interstellar objects with similar physical properties. Below we describe these seven sources individually and discuss the integrated X-ray properties of NGC 4449.

Source 1 (hereafter S1) appears dominated by a point source (see Fig. 3b). Its relatively hard X-ray spectrum (Fig. 6a) is consistent with those commonly seen in X-ray binaries. The number of counts is too low for a meaningful spectral fit. Assuming a Raymond & Smith plasma emission model and a plasma temperature of kT = 1 keV, we estimate an X-ray luminosity of ~ 6 × 10³⁸ ergs s⁻¹ for S1 in the 0.1–2.4 keV band.

Source 2 (hereafter S2) is a known SNR, about 10 times brighter than the X-ray-brightest SNR in the
The X-ray luminosity is inferred from the foreground absorption within NGC 4449.

The RHRI image shows a core with a FWHM of 6′′, which is close to the instrumental FWHM of 6′′ (Blair et al. 1983), superimposed on extended emission. The best fit to the PSPC spectrum gives a plasma temperature of 1.0 keV and an absorption column density of log \( N_H = 20.6 \). The absorption column is significantly higher than the Galactic H I column density, indicating a log \( N_H = 20.4 \) within NGC 4449 itself. The X-ray luminosity of S2 is \( \sim 1 \times 10^{39} \) erg s\(^{-1}\) in the 0.1–2.4 keV band.

Source 3 (hereafter S3) is coincident with the giant H II region CM 16. The RHRI image in Fig. 4b shows a point-like source at S3; its FWHM \( \sim 8′′ \) is slightly more extended than the instrumental width. The spectral energy distribution of S3 (Fig. 7c) is best fitted by a Raymond & Smith model with a plasma temperature of 0.4 keV. This temperature is typical for the plasma emission seen in SNRs, superbubbles, and giant H II regions (Chu et al. 1993, Williams & Blair 1983). Since a SNR at the distance of NGC 4449 will appear unresolved in the RHRI image, and since S3 is more extended than the instrumental FWHM, it is possible that most of the X-ray flux of S3 is emitted by hot, shocked interstellar gas in a luminous SNR and/or within a region \( \sim 200 \) pc across. The low intensity extensions into SGS1, SB3 and SB4, and along FIL28 seen in Fig. 3b will also contribute to the PSPC spectrum of S3. The best Raymond & Smith model fit gives an H I column density of \( 1 \times 10^{20} \) cm\(^{-2}\), indicating little foreground H I absorption within NGC 4449. The X-ray luminosity is \( \sim 8 \times 10^{38} \) erg s\(^{-1}\) in the 0.1–2.4 keV band.

Source 4 (hereafter S4) has a very low surface brightness and extends over a large area to the northwest of the main body of NGC 4449. The spectrum of S4 is clearly soft, and is softer than those of most known sources of diffuse emission. The soft spectrum could be caused by the combination of a low plasma temperature and a low foreground absorption column density. The soft spectrum and the extended distribution of S4 suggest that the X-ray emission originates from hot interstellar gas. S4 has too few counts to warrant a spectral fit. We have re-binned the PSPC spectrum, adopted the Galactic H I column density as the foreground absorption column, and compared the spectrum to those calculated using Raymond & Smith models for plasma temperatures in the range 0.1–0.4 keV. We find a 0.2 keV model best represents the observed spectrum, and estimate an X-ray luminosity of \( 7 \times 10^{38} \) erg s\(^{-1}\) for S4.

Source 5 (hereafter S5) is located in the southern outskirts of NGC 4449. It is superimposed on a relatively quiescent region with no obvious star formation activities. The RHRI image shows an unresolved source, while the PSPC shows a region dominated by diffuse emission. The spectrum of S5 is as soft as that of S4. If the unresolved source is a real point source, the absence of hard X-ray photons implies that the contribution of the point source is very soft, too. This may imply that the point source belongs to the class of supersoft X-ray sources. Most supersoft X-ray sources have the bulk of X-ray emission below 0.5 keV. Alternatively the point source is highly variable, and was very faint during the PSPC observation. In this case we cannot further constrain the nature of the point source. Since the spectral properties of S5 are very similar to those of S4, and the PSPC emission is clearly extended, we think that S5 consists of extended, low-temperature plasma emission and possibly a supersoft point source. Using a plasma temperature of 0.2 keV and the Galactic foreground absorption, we derive an X-ray luminosity of \( \sim 6 \times 10^{38} \) erg s\(^{-1}\) for S5 in the 0.1–2.4 keV band.

Source 6 (hereafter S6) appears extended both in the PSPC image and in the RHRI image. It is located northeast of CM 16 in a region without prominent star formation activities. The X-ray spectrum of S6 is soft, suggesting a hot plasma emission.

Source 7 (hereafter S7) is a very weak point source northwest of NGC 4449. No optical counterpart can be identified in our images. The PSPC spectrum is too noisy to provide useful information. It is not clear if this source is associated with NGC 4449 at all.

The integrated spectrum of NGC 4449 is shown in Fig. 7h. It is clearly a composite spectrum with different temperature components. A single temperature component Raymond & Smith model is plotted over the spectrum to demonstrate this effect. Using this one-temperature Raymond & Smith model fit, we derive a crude estimate of the luminosity of NGC 4449, \( 3.5 \times 10^{39} \) erg s\(^{-1}\) in the 0.1–2.4 keV band.

### 4.2. Relationship between Hot and Warm Interstellar Components

To analyze the large-scale diffuse X-ray emission of NGC 4449, we use the energy bands R1–R7 (Snowden et al. 1992) and made maps in the (R1+R2), (R4+R5), and (R6+R7) bands, which are centered...
roughly at 1/4 keV, 3/4 keV, and 1.5 keV, respectively. As shown in Fig. 3a–c, the images in these three energy bands have different characteristics. In the 1.5 keV band, the emission is dominated by point sources (S1, S2, S3 and S7). In the 3/4 keV band, both point sources (S2, S3, and S7, but not S1) and diffuse sources (S4, S5, and S6) are visible. In the 1/4 keV band, both point sources and diffuse sources are visible, but the point sources become much less prominent. The variation of NGC 4449’s X-ray morphology from hard to soft energy bands is similar to that observed in M101 (Snowden & Pietsch 1995), suggesting that the 1/4 keV band is dominated by diffuse emission from hot interstellar gas.

The Hα image overlaid by X-ray contours of the PSPC data in Fig. 3a, and Hα image overlaid by X-ray contours of the RHRI data in Fig. 3b can be used to relate the hot, X-ray-emitting interstellar gas to the cooler, Hα-emitting interstellar component. The spatial resolution of the PSPC (30′′, or 780 pc) prohibits unambiguous associations of faint diffuse X-ray emission with individual structures that are smaller than ~ 1000 pc. The RHRI has a higher resolution, but it also has a higher background which makes the detection of faint diffuse emission difficult. Thus we are unable to unambiguously identify in NGC 4449 X-ray-bright superbubbles similar to N44 and N51D in the LMC (Chu & Mac Low 1990). The low level emission coinciding with SB3, SB4 and SB8 cannot be claimed as detections. Much longer RHRI integration is required to verify this weak emission. Below we will discuss the hot interstellar gas associated with giant H II regions, supergiant shells, and large-scale Hα filamentary structures.

The giant H II region CM 16 and adjacent superbubbles and filaments form a complex occupying an area more than 1000 pc across. The X-ray source S3 is associated with the CM 16 complex. As described in §4.1, S3 consists of a slightly resolved X-ray source with spectral characteristics suggestive of hot plasma emission. Hot, shocked interstellar gas is commonly seen in giant H II regions, for example, 30 Dor (Wang & Ielfland 1991), NGC 604 (Yang et al. 1996), and NGC 5471 (Williams & Chu 1995). It is interesting to note that the X-ray source S3 in CM 16 not only has an X-ray luminosity within the observed range among these giant H II regions, but also has an emitting volume similar to those of 30 Dor and NGC 604, ~200 pc in diameter. We therefore conclude that the X-ray source S3 in CM 16 is similar to those seen in other giant H II regions. The giant H II region CM 39, on the other hand, does not show the typical X-ray emission expected in giant H II regions. CM 39 is superimposed on diffuse X-ray emission; no discrete X-ray feature can be identified.

Among the five supergiant shells identified in the Hα image of NGC 4449, SGS1 is in a confusing region close to the giant H II region CM 16. The RHRI may show some emission at the position of SGS1, but the surface brightness is much to low to claim a detection (see Fig. 3b). SGS3, SGS4, and SGS5 are not detected. Only SGS2 is clearly visible in the PSPC image, corresponding to the source S4 described in §4.1.

SGS2 appears to be morphologically similar to the supergiant shell LMC2, as both supergiant shells appear to be “blisters” blown by a ridge of active star formation out of the plane, but still confined by the H I disk. However, SGS2 is different from LMC2 in three respects: (1) SGS2 is twice as large as LMC2, (2) the plasma temperature of SGS2 is much lower than that of LMC2, and (3) the X-ray luminosity of SGS2 is up to a factor of 10 higher than that of LMC2 (Points et al. 1997). Thus, SGS2 appears to be the most energetic supergiant shell known!

It is worth noting that the X-ray source S5 might be associated with a not-well-defined supergiant shell. The X-ray properties of S5 imply the existence of an extended component emitted by plasma. This X-ray emitting region is bounded by two long Hα filaments (FIL4 and FIL5 in Fig. 3) in the northwestern and southwestern quadrants. These two long filaments may be the brightest parts of a SGS. Deeper Hα images are needed to confirm the existence of this supergiant shell.

There are still X-ray emitting regions not bounded by obvious interstellar shell structures. Most notably, bright diffuse X-ray emission exists along the ridge of active star formation and extends outward into the adjacent quiescent regions. The X-ray emission along the ridge is visible in both the PSPC and the RHRI images. This emission is particularly bright in the region between the X-ray sources S2 and S3, where the largest number of chimney-like filaments are present. These filaments might be physically associated with the X-ray emitting gas, for example, the region of FIL22, FIL23 and FIL3. These filaments and the diffuse X-ray emission might have be energized by the same massive star population. The X-ray emission region S6 is adjacent to but does not contain star
formation activities. The lack of high concentration of massive stars, shown below in §5.1, suggests that the hot gas is not energized locally and that the hot gas must have been transported from elsewhere. It is likely that an outflow from the star formation region supplies this hot gas. This mechanism might also be responsible for the hot gas in the SGS2 (X-ray source S4) and a possible SGS around the X-ray source S5.

5. Discussion

We have detected diffuse X-ray emission within the largest supergiant shell, within the active star forming regions, and in outflows from the star forming regions in NGC 4449. The hot gas is most likely heated by massive stars via fast stellar winds and supernova blasts. We have used an archival Hubble Space Telescope (HST) WFPC2 F606W (broad V) image of NGC 4449 to examine in detail the distribution of massive stars. Below we relate the existence of hot interstellar gas to the underlying massive stellar population, present a quantitative analysis of the physical properties of the supergiant shell SGS2 and compare our detection of diffuse X-ray emission in NGC 4449 to the results for other irregular galaxies.

5.1. Hot Interstellar Gas and Massive Stars

The massive stars and OB associations in the northern portion of NGC 4449 can be seen in the HST WFPC2 V image presented in Fig. 5a. This region contains our X-ray sources S1, S2, S4, and S6. Fig. 5b shows the RHRI contours overlapped over the HST image. S1 is likely an X-ray binary source, hence will not be discussed further. We only note that the RHRI indicates that S1 is multiple. The other three sources all contain diffuse emission. These sources will be discussed individually.

S2 contains a super-luminous SNR, which appears as a point source in the RHRI image. There is additional diffuse emission extending up to 14″ from the SNR in the NW and SE directions (see Fig. 5b). Our ground-based Hα image shows that the SNR is within a bright H II region. The WFPC2 image shows that this SNR is in a large stellar complex with a particularly high concentration of massive stars at 10-20″ SE of the SNR. This correlation suggests that the hot gas is heated locally by the massive stars.

S4 is a large region of diffuse X-ray emission that coincides with the supergiant shell SGS2. SGS2 is bordered by a ridge of active star formation on the eastern side. The WFPC2 image shows sparsely distributed massive stars within the boundary of SGS2 but a high concentration of massive stars along the eastern border, confirming the intense star formation activity. The low surface density of massive stars within SGS2 casts doubt on the local production of the hot gas. The star formation region at the base of SGS2 thus becomes a likely candidate providing the heating. Indeed, the Hα image reveals multiple radial filaments pointing from the star forming region into SGS2, reminiscent of “chimneys” tracing the paths of energy transport (Heiles 1993). The RHRI overlay image (Fig. 5a) shows diffuse emission extending along the northern part of the bar and north-east of CM 16 where many Hα filaments point away from the bar into SGS2 (see Fig. 5b). This further supports the identification of the radial filaments as chimneys which transport of hot gas upward from the star forming regions in the disk into SGS2. An additional confirmation comes from the echellograms published by HG90. The bright filament FIL3 (object 3 in HG90) appears as a high-velocity spur in their echellograms “c, d, and e”, moving at +150 km s$^{-1}$ with respect to the systemic velocity of NGC 4449 at this position.

The diffuse X-ray source S6 is located in a region with faint featureless Hα emission. Fig. 5b reveals only few massive stars in this region, which are unlikely to be the powering source of the hot gas. The gas is likely transported to this position. Since this region is bordered by active star formation regions on three sides and fragments of filaments (FIL9, FIL10, and FIL38) on the other side, it is possible that the hot gas originates from the star forming regions and is bounded by a shell structure.

These three X-ray sources and the diffuse X-ray emission from the active star formation ridge provide circumstantial evidence that massive stars are responsible for heating the hot gas. In the active star formation region, the hot gas is heated locally. In quiescent regions adjacent to active star formation regions, hot gas can be heated in the active regions and transported to quiescent regions via blow-outs.
5.2. Hot Gas Content of the Supergiant Shell SGS2

We may use the PSPC observation to analyze the physical conditions of the hot gas inside the supergiant shell SGS2. As described in §4.1, the X-ray luminosity \( L_x \) of SGS2 in the 0.1–2.4 keV band is \( 7 \times 10^{38} \) erg s\(^{-1}\), and the plasma temperature is estimated to be \( kT \sim 0.2 \) keV. Assuming that the X-ray emitting hot gas fills the interior of SGS2 (filling-factor of the hot gas \( f \approx 1 \)), we may determine the rms electron density \( n_e \) of the hot gas using the relation

\[
L_x = n_e^2 \Lambda_R(T) V,
\]

where \( \Lambda_R(T) \) is the emissivity in the 0.1–2.4 keV band and \( V \) is the volume. For a temperature of \( kT \sim 0.2 \) keV and a 30% solar abundance, \( \Lambda_R(T) \) is about \( 9.3 \times 10^{-24} \) erg cm\(^3\) s\(^{-1}\) for a Raymond & Smith’s thin plasma emission model. For a diameter of 1800 pc, the volume is \( 3 \times 10^9 \) pc\(^3\). The rms electron density is calculated to be \( 0.03 \) cm\(^{-3}\). This density is higher than that derived for the supergiant shell LMC4, \( 0.01 \) cm\(^{-3}\) (Bomans et al. 1994). Given the higher X-ray surface brightness of SGS2, its higher density is not too surprising.

With the density and volume described above, we derive a total mass of \( 2 \times 10^6 \) M\(_\odot\), and a total thermal energy \( E_{th} \) of \( 1.3 \times 10^{54} \) erg for the X-ray emitting plasma. Note that these values are upper limits for the mass and thermal energy. If the X-ray emitting gas does not fill the entire interior of the SGS \( (f < 1) \), the density would be higher, but the mass and thermal energy would be lower.

The cooling time scale for the hot gas inside SGS2 is about \( 2 \times 10^7 \) yrs, assuming a cooling function of \( 2 \times 10^{-23} n_e^2 \) ergs cm\(^{-3}\) s\(^{-1}\) and \( f = 1 \). The dynamical time scale for SGS2 is in the order of \( 5 \times 10^7 \) yrs, assuming an expansion velocity of 20 km s\(^{-1}\) and a radius of 2 kpc. Note that this timescale represents a rough upper limit for the dynamical age of SGS2, since it does not incorporate the acceleration due to expansion into a density gradient (e.g. Mac Low et al. 1993). The comparison between the cooling timescale and the dynamical timescale implies that energy input from the recent star formation event is needed to maintain the hot gas inside SGS2.

Future analysis of the energy budget based on detailed stellar content and detailed nebular dynamics together with higher sensitivity and resolution X-ray data are needed to understand if SGS2 is indeed powered by the star forming region at its base.

5.3. Comparison to Other Starforming Dwarf Galaxies

NGC 4449 is the first normal star forming irregular galaxy besides the LMC in which diffuse X-ray emission from hot gas is detected. The origins of diffuse X-ray emission in NGC 4449 are similar to those in the LMC (Chu 1996), such as giant HII region, supergiant shells, superbubble, and quiescent regions with no recent star formation activities. The supergiant shell SGS2 in NGG 4449 is more extreme in its properties than all LMC supergiant shells. We find evidence indicating that energy is being pumped into SGS2 in NGC 4449; similar energy input is seen in the supergiant shell LMC 2 (Points et al. 1997). The mechanisms for producing diffuse X-ray emission appear to be similar for NGC 4449 and the LMC.

We can also compare NGC 4449 to more active star forming irregular galaxies. X-ray observations of four starbursting irregular galaxies have been reported: NGC 1569, NGC 1705, NGC 5253, and UGC 6456. The amorphous irregular galaxies NGC 5253 (Martin & Kennicutt 1993) and NGC 1705 (Hensler et al. 1996) show diffuse X-ray emission near the starburst region where super starclusters have been detected (Meurer et al. 1993); furthermore the diffuse emission in NGC 1705 seems to be bounded by H\(_\alpha\) shells. The blue compact dwarf galaxies NGC 1569 (Heckman et al. 1993) and UGC 6456 (Papaderos et al. 1994) show diffuse X-ray emission at large distances from the starburst regions, which has been interpreted as outflows. Interestingly, two super starclusters are found in the starburst core of NGC 1569 (O’Connell et al. 1994).

All of these four galaxies show hot gas produced predominantly in their starburst regions. This is similar to what we see in NGC 4449 and the LMC, although star formation in the latter two galaxies is more spreaded over the galaxy and at an overall lower level. The two low-mass galaxies with most intense star formation (NGC 1569 and UGC 6456) show large-scale outflow of hot gas. This is similar what we see in SGS2 and the diffuse X-ray sources (such as S6) in NGC 4449. This indicates that outflows from intense star formation regions may be common in star forming irregular galaxies.

Our analysis of NGC 4449 indicates that its production of hot gas is similar to that of the LMC and...
other active star forming irregular galaxies. However, we still do not know why the SMC does not show appreciable diffuse X-ray emission despite its moderate star formation activity. The irregular galaxy Ho IX might have similar X-ray properties as the SMC. Diffuse X-ray emission has reported in [Miller 1995], however, the hard X-ray spectrum of this source is more consistent with that of an X-ray binary; no soft X-ray component is present to indicate the existence of hot interstellar gas. It is possible that a certain level of star formation activity is required to produce the hot gas responsible for the diffuse X-ray emission. A larger sample of irregular galaxies with different levels of star formation activity need to be studied in order to determine whether and how star formation activity governs the level of diffuse X-ray emission in irregular galaxies.

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A. Appendix

To ease the discussion of Hα features in this paper, we have identified and listed in Tables A1 and ?? the principal diffuse Hα features in NGC 4449. Table A1 lists the supergiant shells and superbubbles of NGC 4449. For each shell structure the central coordinates were determined, using the STSDAS astrometry package and the digital sky survey for the astrometric reduction. We also measured the angular sizes of the shells and converted them to linear sized assuming a distance of 5.4 Mpc. Brief comments are also given. Table ?? lists the principal Hα filaments in NGC 4449. The list is not complete, especially in the very crowded central region. The coordinates of the brightest parts or the centers of the filaments are given.
REFERENCES

Bajaja, E., Huchtmeier, W.K., & Klein, U. 1994, A&A, 285, 385

Blair, W.P., Kirshner, R.P., & Winkler, P.F. 1983, ApJ, 272, 84

Bomans, D.J., & Hopp, U. 1993, in “Star Forming Galaxies and Their Interstellar Medium,” eds. J. Franco, F. Ferrini, G. Tenorio-Tagle, Cambridge Univ. Press, p. 159

Bomans, D.J., Dennerl, K., & Kürster, M. 1994, A&A, 283, L21

Bomans, D.J., Chu, Y.-H., Snowden, S.L. et al. 1997, in prep.

Chu, Y.-H. 1996, in “Röntgenstrahlung from the Universe,” eds. H.U. Zimmerman, J.E. Trümper, and H. Yorke, p.311

Chu, Y.-H., & Mac Low, M.-M. 1990, ApJ, 365, 510

Chu, Y.-H., Mac Low, M.-M., Garcia-Segura, G., Wakker, B., & Kennicutt, R.C. 1993, ApJ, 414, 213

Crillon, R., & Monnet, G. 1969, A&A, 1, 449

David, L. P., Harnden, F., Jr., Kearns, K. E., & Zombeck, M. V. 1996, The ROSAT High Resolution Imager (HRI) Calibration Report, published by U.S. ROSAT Science Data Center/SAO

Dettmar, R.-J. 1990, A&A 232, L15

Domgörgen, H., & Mathis, J.S. 1994, ApJ, 428, 647

Fabbiano, G. 1988, ApJ, 325, 544

Heiles, C. 1984, ApJS, 55, 585

Heiles, C. 1993, Reviews in Modern Astrophysics, ed. G. Klare, Astronomische Gesellschaft, Vol. 6, p. 19

Hensler, G., Samland, M., Theis, Ch., & Burkert, A. 1994, in Panchromatic View of Galaxies – their Evolutionary Puzzle, eds.: G. Hensler, Ch. Theis, J. Gallagher, Editions Frontieres, p. 341

Hensler, G., Dickow, R., Junkes, N., & Gallagher, J.S. 1996, in Röntgenstrahlung from the Universe, eds.: Zimmermann, H.U., Trümper, J., Yorke, H, MPE report 263, p. 379

Hill, R., Home, A.T., Smith, A.M., Bruhweiler, F.C., Cheng, K., Hintzen, P.M.N., & Oliversen, R.J. 1994, ApJ, 430, 568

Hunter, D.A. 1994, AJ, 107, 565

Hunter, D.A., & Gallagher, J.S. 1990, ApJ, 362, 480 (HG90)

Hunter, D.A., & Gallagher, J.S. 1992, ApJ, 391, L9 (HG92)

Kaler, J.B. 1976, ApJS, 31, 517

Kaler, J.B. 1983, ApJ, 264, 594

Klein, U., & Gräve, R. 1986, A&A, 161, 155

Klein, U., Hummel, E., Bomans, D.J., & Hopp, U. 1996, A&A, 313, 396

Lequeux, J., Peimbert, M., Rayo, J.F., Serrano, A., & Torres-Peimbert, S. 1979, A&A, 80, 155

Long, K.S., Charles, P.A., Blair, W.P., & Gordon, S.M. 1996, ApJ, 466, 750

Mac Low, M.-M., McCray R., & Norman, M.L. 1989, ApJ, 337, 141

Marconi, G., Matteucci, F., & Tosi, M. 1994, MNRAS, 270, 35

Martin, C.L., & Kennicutt, R.C. 1995, ApJ, 447, 171

Meurer, G.R., Heckman, T.M., Leitherer, C., Kinney, A., Robert, C., & Garnett, D.R. 1995, AJ, 110, 2665

Miller, B.W. 1995, ApJ, 446, L75

Morrison, R. & McCammon, D. 1983, ApJ, 270, 119

O’Connell, R.W., Gallagher, J.S., Hunter, D.A. 1994, ApJ, 433, 650

Oey, M.S., & Massey, P. 1995, ApJ, 452, 2100

Points, S.D. et al. 1997, in prep.

Papaderos, P., Fricke, K.J., Thuan, T.X., & Loose, H.-H. 1994, A&A, 291, L13
Rand, R.J., Kulkarni, S.R., & Hester, J.J. 1990, ApJ, 352, L1, erratum ApJ, 362, L35
Raymond, J.C., & Smith, B.W. 1977, ApJS, 35, 419
Sabbadin, F. & Bianchini, A. 1979, PASP, 91, 280
Schmidt, K., & Boller, T. 1992, AN, 313, 329
Seaquist, E.R., & Bignell, R.C. 1978, ApJ, 226, L5
Skillman, E.D. 1994, in: Violent Star Formation For 30 Dor to QSOs, ed. G. Tenorio-Tagle, Cambridge University Press, p. 168
Skillman, E.D., Bomans, D.J., & Kobulnicky, H.A. 1997, ApJ, 474, 205
Slavin, J.D., Shull, J.M., & Begelman, M.C. 1993, ApJ, 407, 83
Snowden, S.L., & Chu, Y.-H. 1996, in ROSAT Newsletter, No. 13, p.30
Snowden, S.L., McCammon, D., Burrows, D.N., & Mendenhall, J.A. 1992, ApJ, 424, 714
Snowden, S.L., & Petre, R. 1994, ApJ, 436, L123
Snowden, S.L., & Pietsch, W. 1995, ApJ, 452, 627
Snowden, S.L. 1996, BAAS, 188, 5103
Tully, R.B. 1988, “Nearby Galaxies Catalog”, Cambridge Univ. Press
van Woerden, H., Bosma, A., & Mebold, U. 1975, in “La Dynamique des Galaxies Spirales,” ed. L. Weliachew, Edition du CNRS, p. 483
Wang, Q., & Helfand, D.J. 1991, ApJ, 370, 541
Will, J.-M., Bomans, D.J., & Dieball, A. 1997, A&A, in press
Williams, R.M., & Chu, Y.-H. 1995, ApJ, 439, 132
Yang, H., Chu, Y.-H., Skillman, E.D., & Terlevich, R. 1996, AJ, 112, 146

Figure Captions

Fig. 1.— Red continuum image of NGC 4449, taken with the Calar Alto 3.5m telescope.

Fig. 2.— Continuum-subtracted Hα image of NGC 4449. Shells and filaments are prevalent in the main body of NGC 4449. Faint shells and filaments extend to large distances from the main body.

Fig. 3.— Continuum-subtracted Hα image of NGC 4449 with the principal shells and filaments marked.

Fig. 4.— (a) Smoothed ROSAT PSPC image of NGC 4449 in the 0.1–2.4 keV energy band, displayed with the same image scale as the optical images in Figs. 1 and 2. (b) Smoothed ROSAT HRI image of NGC 4449, displayed with the same image scale as the images in Figs. 1, 2, and 4a.

Fig. 5.— Broad-band (0.1–2.4 keV), un-smoothed PSPC image of NGC 4449. The seven source regions are marked. The large un-numbered circle encloses the region for the entire NGC 4449 galaxy.

Fig. 6.— (a) Continuum-subtracted Hα image of NGC 4449 overlaid by X-ray contours derived from the broad-band (0.1–2.4 keV) ROSAT PSPC image. The same continuum-subtracted Hα image of NGC 4449 overlaid by the ROSAT HRI image.

Fig. 7.— ROSAT PSPC energy distributions of the seven X-ray sources and of the entire NGC 4449 galaxy. Sources 2 and 3 have sufficient counts for spectral fits. The best-fit Raymond & Smith models are over-plotted. The one-temperature component Raymond & Smith model fit for the entire galaxy is clearly an over-simplification. This fit is used for only a crude estimate of the luminosity of NGC 4449.

Fig. 8.— ROSAT PSPC images of NGC 4449 in (a) the (R1+R2) band centered at 1/4 keV, (b) the (R4+R5) band centered at 3/4 keV, and (c) the (R6+R7) band centered at 1.5 keV.

Fig. 9a.— HST WFPC2 image of NGC 4449, taken through the F606W (broad V) filter.

Fig. 9b.— HST WFPC2 image of NGC 4449, taken through the F606W (broad V) filter. The overlaid contours are X-ray emission taken from the RHRI image.
### Table 1
**Basic X-ray Data of the Sources**

| Region | Counts | $\log N_H$ [cm$^{-2}$] | kT [keV] | $L_X$(0.1-2.4 keV) [$10^{38}$ erg s$^{-1}$] | $L_X$(0.5-2.4 keV) [$10^{38}$ erg s$^{-1}$] |
|--------|--------|-------------------|--------|------------------|------------------|
| 1      | $98 \pm 17$ | 20.2              | 1.0    | 6                | 2                |
| 2      | $195 \pm 21$ | 20.6$^a$         | 1.0$^a$| 13               | 8                |
| 3      | $181 \pm 20$ | 20.2$^a$         | 0.4$^a$| 8                | 5                |
| 4      | $116 \pm 20$ | 20.2              | 0.2    | 7                | 2                |
| 5      | $98 \pm 18$  | 20.2              | 0.2    | 6                | 2                |
| 6      | $101 \pm 17$ | 20.2              | 0.7    | 5                | 4                |
| 7      | $14 \pm 13$  | 20.2              | 0.7    | 1                | 1                |
| **All** | $947 \pm 55$ | 20.2              | 0.6    | 35               | 25               |

$^a$The $\log N_H$ and kT values are result from a spectral spectra fit.

$^b$Integrated over the entire NGC 4449 galaxy.

### Table A1
**List of the Supergiant Shells and Superbubbles in NGC 4449**

| Source | RA (2000.0) | DEC (2000.0) | Diameter [pc] | Comment |
|--------|-------------|--------------|---------------|---------|
| SGS1   | 12 28 07.8  | 44 04 50     | 520           | structure 1 in HG90, expanding |
| SGS2   | 12 28 06.4  | 44 06 25     | 1830          | structure 5 & 6 in HG92         |
| SGS3   | 12 27 56.6  | 44 05 40     | 500           |                                    |
| SGS4   | 12 28 05.5  | 44 05 00     | 1060          | diffuse                           |
| SGS5   | 12 28 17.7  | 44 05 10     | 1295          | diffuse, uncertain                |
| SB1    | 12 28 20.9  | 44 06 11     | 360           |                                    |
| SB2    | 12 28 09.7  | 44 06 54     | 340           |                                    |
| SB3    | 12 28 10.1  | 44 05 09     | 235           | discussed in H94; part of CM16?   |
| SB4    | 12 28 10.4  | 44 05 06     | 475           | structure 2 in HG90; part of CM16; SGS6? |
| SB5    | 12 28 13.8  | 44 05 02     | 390           |                                    |
| SB6    | 12 28 05.4  | 44 04 16     | 255           | attached filament                 |
| SB7    | 12 28 06.6  | 44 03 41     | 255           |                                    |
| SB8    | 12 28 06.7  | 44 04 23     | 235           |                                    |
| SB9    | 12 28 13.6  | 44 04 33     | 465           | SGS7?                             |
### Table A2

**List of the Principal Hα Filaments in NGC 4449.**

| Source | RA (2000.0) | DEC (2000.0) | Comment |
|--------|-------------|--------------|---------|
| FIL1   | 12 28 13.2  | 44 06 34     | partly structure 4 in HG90 |
| FIL2   | 12 28 07.7  | 44 05 41     |         |
| FIL3   | 12 28 09.6  | 44 05 58     | partly structure 3 in HG90 |
| FIL4   | 12 28 08.0  | 44 04 20     |         |
| FIL5   | 12 28 08.2  | 44 03 42     |         |
| FIL6   | 12 28 11.7  | 44 05 04     | interlocking shells ? |
| FIL7   | 12 28 15.2  | 44 05 52     |         |
| FIL8   | 12 28 14.4  | 44 05 59     | group of filaments |
| FIL9   | 12 28 18.0  | 44 05 38     |         |
| FIL10  | 12 28 19.0  | 44 06 14     |         |
| FIL11  | 12 28 17.0  | 44 06 29     |         |
| FIL12  | 12 28 17.8  | 44 06 59     | superbubble ? |
| FIL13  | 12 28 14.4  | 44 06 52     |         |
| FIL14  | 12 28 14.9  | 44 06 59     |         |
| FIL15  | 12 28 12.4  | 44 07 11     | ‘intersecting’ filaments |
| FIL16  | 12 28 11.6  | 44 07 04     |         |
| FIL17  | 12 28 10.1  | 44 07 06     |         |
| FIL18  | 12 28 08.1  | 44 06 51     |         |
| FIL19  | 12 28 09.1  | 44 06 30     |         |
| FIL20  | 12 28 12.1  | 44 06 36     |         |
| FIL21  | 12 28 12.1  | 44 06 24     | superbubble ? |
| FIL22  | 12 28 10.1  | 44 06 19     | ‘intersecting’ filaments |
| FIL23  | 12 28 11.5  | 44 06 08     |         |
| FIL24  | 12 28 10.9  | 44 05 59     | complex web with FIL3 and 25 |
| FIL25  | 12 28 10.3  | 44 05 45     | open shell ? |
| FIL26  | 12 28 10.3  | 44 05 38     | open shell ? |
| FIL27  | 12 28 09.8  | 44 05 31     |         |
| FIL28  | 12 28 09.1  | 44 05 28     | part of CM16 ? |
| FIL29  | 12 28 08.2  | 44 05 16     | open shell?: part of CM16 ? |
| FIL30  | 12 28 12.1  | 44 05 21     | interlocking shells ? |
| FIL31  | 12 28 12.3  | 44 04 52     |         |
| FIL32  | 12 28 15.1  | 44 04 53     | group of filaments |
| FIL33  | 12 28 14.0  | 44 06 17     | group of filaments |
| FIL34  | 12 28 12.4  | 44 06 51     |         |
| FIL35  | 12 28 15.0  | 44 06 31     | multiple filaments |
| FIL36  | 12 28 17.1  | 44 07 13     |         |
| FIL37  | 12 28 07.2  | 44 05 53     |         |
| FIL38  | 12 28 17.8  | 44 05 30     |         |
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