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HOT GAS IN THE LARGE MAGELLANIC CLOUD

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RESUMEN

Debido a su cercanía, su orientación casi de frente y la baja extinción externa e interna, la Nube Mayor de Magallanes (LMC) es un laboratorio excelente para estudiar la estructura física del medio interestelar (ISM). Estudios del gas de la LMC en el óptico y en el radio han mostrado estructuras interestelares que van de unos cuantos parsecs hasta más de 1000 pc. Los mosaicos hechos con *ROSAT* en rayos-X muestran la abundancia del gas caliente a 10^6 K, el cual a veces está rodeado de grandes cascarones, pero el resto no parece estar asociado a ninguna estructura interestelar visible. Las observaciones de rayos-X han sido analizadas para determinar las condiciones físicas del gas caliente. Para determinar su origen, la distribución del gas caliente puede ser comparada con la del gas más frío y con la de las estrellas masivas. Observaciones UV de líneas de absorción de iones de alta ionización como C IV, N V y O VI, pueden ser usadas para estudiar las interfases del gas a 10^6 K con el gas más frío y para dar restricciones sobre la localización de ambos a lo largo de la línea de visión.

ABSTRACT

The Large Magellanic Cloud (LMC) offers an excellent laboratory to study the physical structure of the interstellar medium (ISM) because of its proximity, nearly face-on orientation, and small foreground and internal extinction. Optical and radio surveys of the LMC ISM have revealed interstellar structures of sizes ranging from a few parsecs to over 1000 parsecs. *ROSAT* X-ray mosaics of the LMC have detected abundant 10^6 K hot gas, some of which is bounded by large shell structures while the rest does not appear to be associated with any visible interstellar structure. The X-ray observations have been analyzed to determine the physical conditions of the hot gas. The distribution of the hot gas can be compared to those of the cooler gas and massive stars, in order to determine the production mechanism of the hot gas. UV observations of interstellar absorption lines of high ions, such as C IV, N V, and O VI, can be used to study the interfaces between the 10^6 K gas and cooler ionized gas, and to provide constraints on the location of 10^6 K gas with respect to the cooler gas along the line of sight.

Key Words: **H II REGIONS — ISM: BUBBLES — ISM: STRUCTURE — MAGELLANIC CLOUDS — SUPERNOVA REMNANTS**

1. INTRODUCTION

The structure of the interstellar medium (ISM) is dynamic and complex. The ISM forms massive stars, and massive stars in turn inject ionizing radiation and mechanical energy into the ISM. The interplay between the ISM and massive stars produces a multi-phase structure of the ISM. Numerous models have been proposed to explain the structure of the ISM in the Milky Way Galaxy. As we reside in the Local Bubble in the disk of the Galaxy, it is extremely difficult to decipher observations of the ISM in the Galactic plane because of the wavelength dependence of extinction, uncertain distances, and confusion along the line of sight. Therefore, it has been constantly debated which model most accurately describes the structure of the ISM in our Galaxy.

The above mentioned problems, faced by the Galactic ISM studies, are not as limiting for studies of the ISM

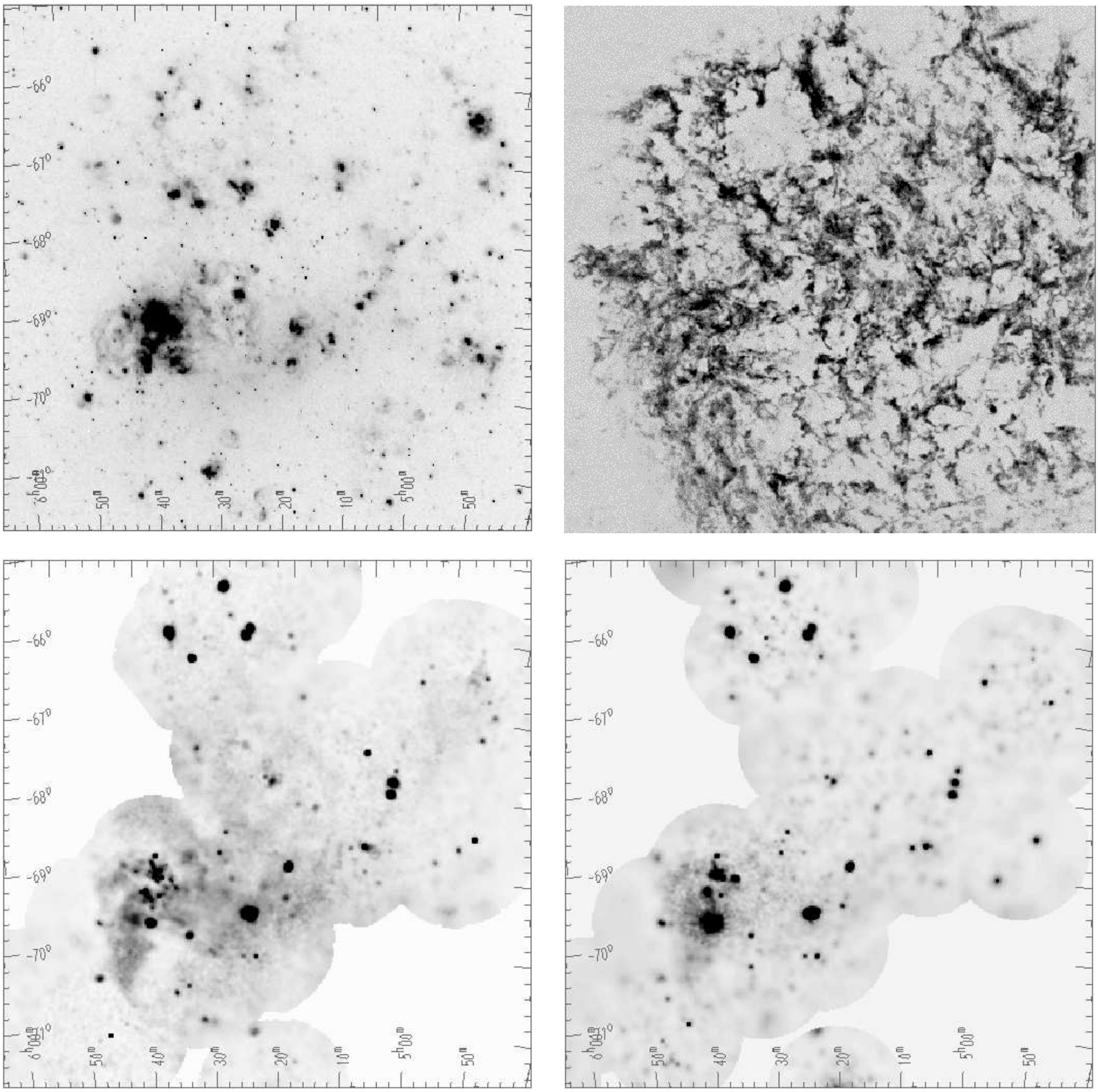

Fig. 1. Images of the ISM in the Large Magellanic Cloud. (*Upper Left*) Hα image showing the 10^4 K ionized gas. (*Upper Right*) H I 21-cm line image showing the atomic H I gas. (*Lower Left*) *ROSAT* PSPC X-ray mosaic in the 0.44–1.21 keV band. (*Lower Right*) *ROSAT* PSPC X-ray mosaic in the 1.05–2.04 keV band. The X-ray images show the 10^6 K ionized gas. The diffuse X-ray emission is better seen in the soft energy band, while point X-ray sources are more prominent in the hard energy band. The Hα and H I images were provided by Sungeun Kim; the PSPC mosaics were provided by Steve Snowden.

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in our neighboring galaxy, the Large Magellanic Cloud (LMC). With a nearly face-on view, the LMC can be studied with little confusion along each line of sight. At a small and known distance, 50 kpc, the LMC can be observed with high, sub-parsec spatial resolution. With a small internal and foreground extinction, the LMC remains highly visible even at soft X-ray and UV wavelengths. Both interstellar structures and their underlying massive stars can be resolved and studied in great detail. The LMC thus provides an excellent laboratory to study physical processes and physical structures of the ISM.

Optical and radio surveys of the LMC have revealed magnificent views of the ionized and neutral interstellar gas in the LMC. Figure 1 shows images of the ionized 10^4 K gas, ionized 10^6 K gas (Snowden & Petre 1994), and the neutral atomic H I gas of the LMC (Kim et al. 1998). It is clear that the LMC is abundant in interstellar gas and active in star formation. Massive stars have excavated interstellar shell structures of scale sizes from a few parsecs to over 1000 parsecs. I will examine the production of hot gas in these interstellar structures and further use observations of the hot gas to probe the physical structure and conditions of the ISM.

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2. ENERGY SOURCES OF THE HOT GAS

Massive stars dynamically interact with the ambient ISM via fast stellar winds during their lifetime and supernova blasts at the end of their evolution. Both interactions produce shock-heated gas at temperatures $\geq 10^6$ K. The hot gas is usually confined in interstellar shells, whose sizes are determined by their massive stellar content. If blowouts/breakouts occur, the hot gas may be injected into the halo or low-density regions in the disk.

An isolated massive star can blow a bubble with its fast stellar wind. As the star ends its life in a supernova explosion, the supernova ejecta will interact with the ambient medium and form a supernova remnant (SNR). Single-star bubbles and SNRs are observed to have sizes of a few to a few tens parsecs.

Clustered massive stars, such as an OB association, can collectively form a superbubble. As a large number of massive stars contribute stellar winds and supernova ejecta to its formation, a superbubble is larger, typically a few tens to a couple hundreds of parsecs across.

If multiple generations of clustered massive stars are formed close to one another, a supergiant shell with a diameter approaching 1000 pc may form. Supergiant shells are the largest structures in the ISM, and may provide the most efficient means to pump hot gas into the halo.

It has been commonly cited that stellar winds are as important a source of energy for the ISM as supernovae; however, a simple order-of-magnitude comparison between stellar wind energy and supernova energy shows that supernova energy *is* higher than the cumulative stellar wind energy. For a stellar wind terminal velocity of 2000 km s^{-1} and a mass loss rate of 10^{-7} $M_\odot$ yr^{-1}, the cumulative mechanical energy of the wind in 10^6 yr is 4×10^{48} ergs. These numbers can be adjusted for stars with different masses, but it would be very difficult to produce more stellar wind energy during the stellar lifetime than the canonical explosion energy of a supernova, 10^{51} ergs. Thus, it is conceivable that supernovae play a more important role than stellar winds in the formation of large interstellar shell structures and in the production of hot gas. As I illustrate in the rest of the paper, SNRs are responsible for most of the X-ray emission detected in interstellar shells.

3. HOT GAS ∈ THE DISK

3.1. *Bubbles and Supernova Remnants*

It is commonly accepted that fast stellar winds can sweep up the ambient medium and form wind-blown bubbles. Wind-blown bubbles are frequently observed around evolved massive stars, such as Wolf-Rayet stars and luminous blue variables; however, no main sequence O stars are known to be surrounded by bubbles. A common scapegoat for the absence of bubbles around main sequence O stars is the low density of the ambient medium, which prevents the formation of an observable bubble. To determine what is really responsible for the absence of bubbles around main sequence O stars, we need to look into young H II regions where gas density is high and the embedded stars are still on the main sequence.

The H II region N11B in the LMC encompasses the OB association LH10, which contains at least three O3 stars (Parker et al. 1992). As O3 stars are the earliest-type and the most massive stars, their presence in an OB association implies that the OB association is young and that perhaps no supernovae have occurred.

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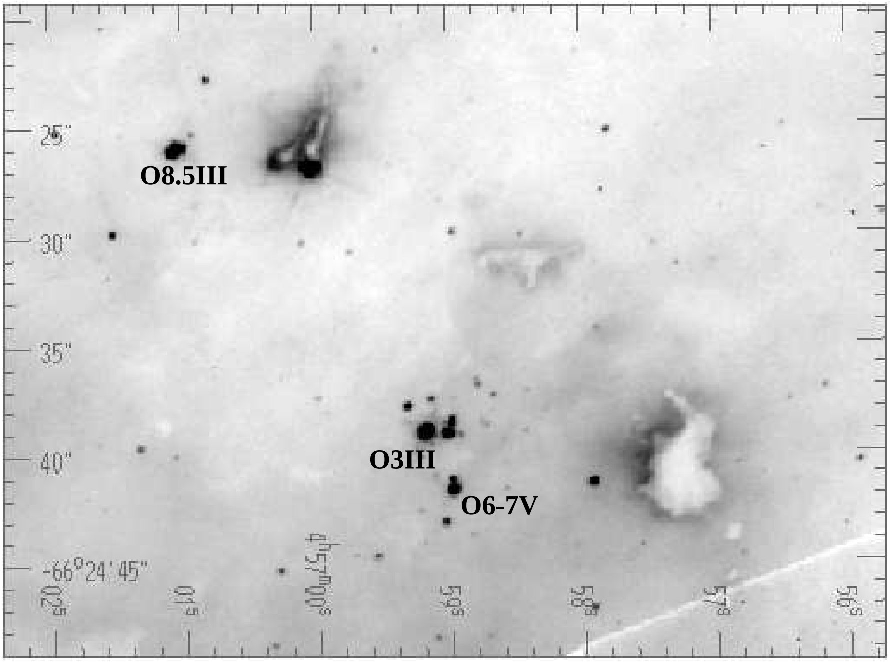

Fig. 2. *HST* WFPC2 Hα image of a portion of N11B. Clearly visible are Bok globules of sizes 0.2–1 pc, with their surface ionized by the UV fluxes from the O stars. No wind-blown bubbles are seen around these O stars.

Indeed, LH10 contains mostly main sequence OB stars (Parker et al. 1992) and the H II region shows no trace of SNR shocks (Rosado et al. 1996). N11B is thus a prime site to study the interaction between stellar winds and the ISM, and to probe whether stellar winds of main sequence O stars can blow bubbles in the ISM.

The *Hubble Space Telescope* (*HST*) has been used to take high-resolution images of N11B. The WFPC2 images of N11B show bright Hα and [O III] emission with complex variations in surface brightness; however, no wind-blown bubbles can be recognized. Figure 2 shows a portion of the WFPC2 Hα image of N11B. Bok globules of sizes 0.2–1 pc ($\sim 1'' - 5''$) are seen bathed in the ionization radiation field of the O stars; however, they do not seem to be disturbed by the stellar winds of the O stars. Where are the wind-blown bubbles?

The formation of small wind-blown bubbles directly affects the formation of superbubbles. Superbubbles are frequently seen around older OB associations. It has been surmised whether an OB association first forms small bubbles around individual stars and the small bubbles coalesce into a superbubble, or a small superbubble is formed around the entire OB association right from the start, and the small superbubble grows in size as time goes on. The image of N11B does not shed much light on this issue. If the O3 star in Figure 2 has ended its life in supernova, its SNR may reveal more clearly the structure of the H II region. As luck has it, the SNR N63A in the LMC may represent exactly such a situation.

The SNR N63A is located in the H II region N63 around the OB association LH83 (Fig. 3). The size of the SNR indicated by the X-ray and radio emission is much larger than the size determined from optical images. Most of the radio and X-ray emission does not seem to have optical counterparts. *HST* WFPC2 images of N63A were obtained in the Hα and [S II] lines (Chu et al. 1999). These images reveal not only the shocked clouds, that were previously identified with ground-based images, but also small shocked cloudlets evaporating in the SNR interior (see Fig. 3). The X-ray peak on the eastern part of the SNR is coincident with several small cloudlets of sizes 0.1–1 pc and densities a few 10^2 H cm^{-3} (Chu et al. 1999). These cloudlets are embedded in the SNR interior and their evaporation raises the density of hot gas and the X-ray emission.

As the cloudlets in the interior of N63A are clouds evaporating in hot gas discovered for the first time, Chu (this meeting) requested the \$5 bill that was claimed by Cox (1995) to have been framed in Mexico City and waiting for the first discoverer of evaporating clouds. After a heated discussion, Franco and Cox (this meeting) concluded that either Cox never gave Franco a \$5 bill to frame or the \$5 had been transformed into Cox's

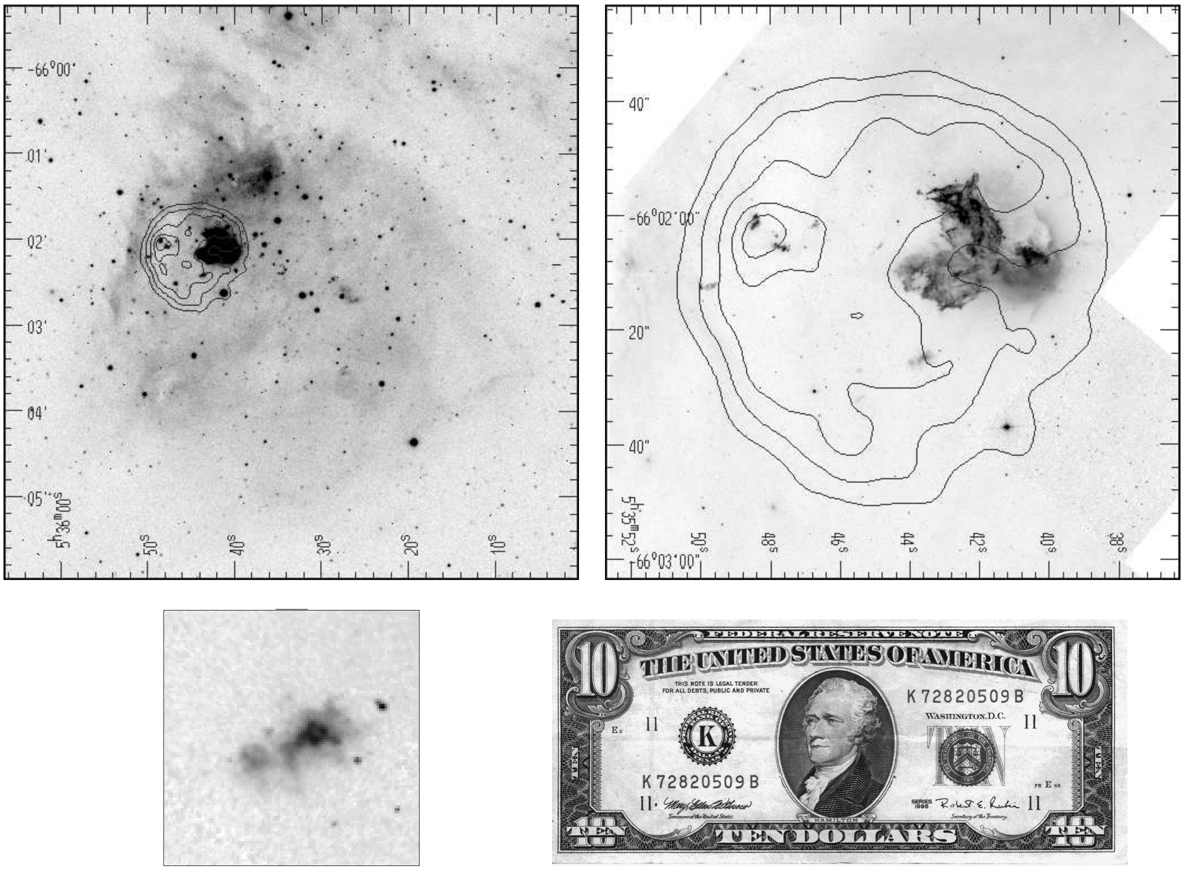

Fig. 3. (*Top Left*) *HST* WFPC2 Hα image of the H II region N63 around the OB association LH83 overlaid with X-ray contours extracted from a *ROSAT* High Resolution Imager observation in the 0.1–2.0 keV band. (*Top Right*) A close-up on the SNR N63A. These two figures are adopted from Chu et al. (1999). (*Bottom Left*) A close-up of an evaporating cloud. The field size is $10'' \times 10''$. (*Bottom Right*) The \$10 bill presented by D. Cox to the discoverer of the first evaporating cloud embedded in hot gas. This bill has been framed and placed on Y.-H. Chu's desk in Urbana, Illinois.

midnight cerveza and consumed. Although Cox was not 100% convinced that the cloudlets in N63A are indeed evaporating, he doled out a \$10 bill (see Fig. 3), which has been framed and placed on Chu's desk in Urbana, Illinois.

The cloudlets inside the SNR N63A are similar to the Bok globules in the H II region N11B. It is conceivable that after an O3 star in N11B (Fig. 2) explodes as a supernova, the Bok globules will be engulfed within the SNR and become the evaporating clouds similar to those seen inside N63A. As the SNR N63A does not include the other members of the OB association LH83, it does not seem that there is a small superbubble around the OB association LH83. It is possible that the formation of a superbubble is initiated by the first supernova. Further studies are needed to pinpoint how superbubbles are formed.

X-ray observations of hot gas in SNRs are useful not only in studying the physical structure of SNRs, but also in probing the supernova progenitor's circumstellar/interstellar environments, especially for young SNRs (Williams 1999; Williams et al. 1999). Some young SNRs show X-ray emission over a large spatial extent. For example, the young oxygen-rich SNR N132D (Fig. 4) has an expansion velocity of ~ 3700 km s^{-1}, yet its radius is large, ~ 12 pc (Morse, Winkler, & Kirshner 1995; Morse et al. 1996). The large expansion velocity and shell size of N132D suggest that the supernova has exploded in the cavity of a bubble blown by the progenitor, and that the SNR shock quickly passes through the low-density interior and has reached the dense shell.

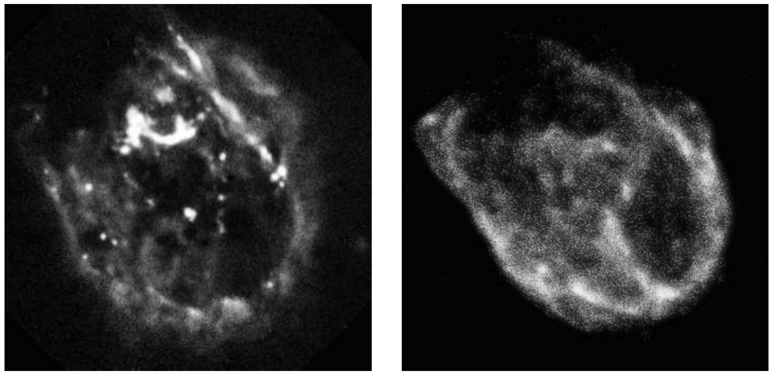

Fig. 4. (*Left*) *HST* WFPC2 [O III] image of the young SNR N132D. (*Right*) *Chandra* High Resolution Camera image of N132D in 0.1–10 keV. The scales of these two images are similar but not identical.

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3.2. *Superbubbles, Giant H II Regions, and Supergiant Shells*

X-ray emission from LMC superbubbles was first detected with Einstein observations (Chu & Mac Low 1990; Wang & Helfand 1991). The X-ray luminosities are much higher than the theoretical predictions for superbubbles. Thus it has been suggested that SNRs shocking the inner walls of the superbubble shell are responsible for heating the gas and generating the excess X-ray emission. Subsequent *ROSAT* and *ASCA* observations of LMC superbubbles have established that some superbubbles have broken out to low-density regions (e.g., N44 - Chu et al. 1993; Magnier et al. 1996), and that superbubbles without recent supernovae are X-ray-dim and the 3σ upper limit of their X-ray luminosities are comparable to those expected in theoretical models (Chu et al. 1995). Deep X-ray observations are needed to verify whether the X-ray emission from X-ray-dim superbubbles are indeed consistent with the predictions.

It is difficult to confirm the SNR shocks in X-ray-bright superbubbles. High-dispersion spectroscopic observations of the Hα emission line fail to detect any high-velocity material in these superbubbles (Chu 1997). High-resolution *HST* WFPC2 images of superbubbles show the outer interstellar shocks but do not show any SNR-shocked material in the superbubble interior (Chen et al. 2000). Only high-dispersion UV spectroscopic observations show high-velocity components in the high-ionization lines, such as C IV and N V, in the X-ray-bright superbubble N51D (de Boer & Nash 1982; Chu et al. 1994). These results are all consistent with the hypothesis that in X-ray-bright superbubbles SNR shocks have interacted with only the low-density interiors.

Figure 5 shows a pair of Hα and X-ray images of the 30 Dor complex and its vicinity. The X-ray image is a mosaic of *ROSAT* High Resolution Imager (HRI) observations of the LMC (Chu & Snowden 1998). This X-ray image has such a high angular resolution that point sources can be unambiguously separated from the diffuse emission. It is clear that diffuse X-ray emission is detected in superbubbles, the giant H II region 30 Dor, and supergiant shells in the LMC.

The hot gas in 30 Dor can be easily explained. Hα images of 30 Dor show a multiple-shell structure; each shell is similar to an X-ray-bright superbubble, but high-velocity shocked material has been detected in 30 Dor (Chu & Kennicutt 1994), and high-velocity components in interstellar C IV absorption lines are seen (Chu et al. 1994). The hot gas in 30 Dor must have been heated by SNRs.

The supergiant shell LMC2 (Fig. 5) has the highest X-ray surface brightness among all supergiant shells in the LMC. The kinematics and physical structure of LMC2 has been studied in great detail by Points et al. (1999). Using the kinematic information derived from H I 21-cm line and Hα emission line observations and comparing X-ray and optical images, they conclude that LMC2 is not an expanding shell, and its hot gas comes from local SNR heating and outflows from the star formation regions along its western ridge.

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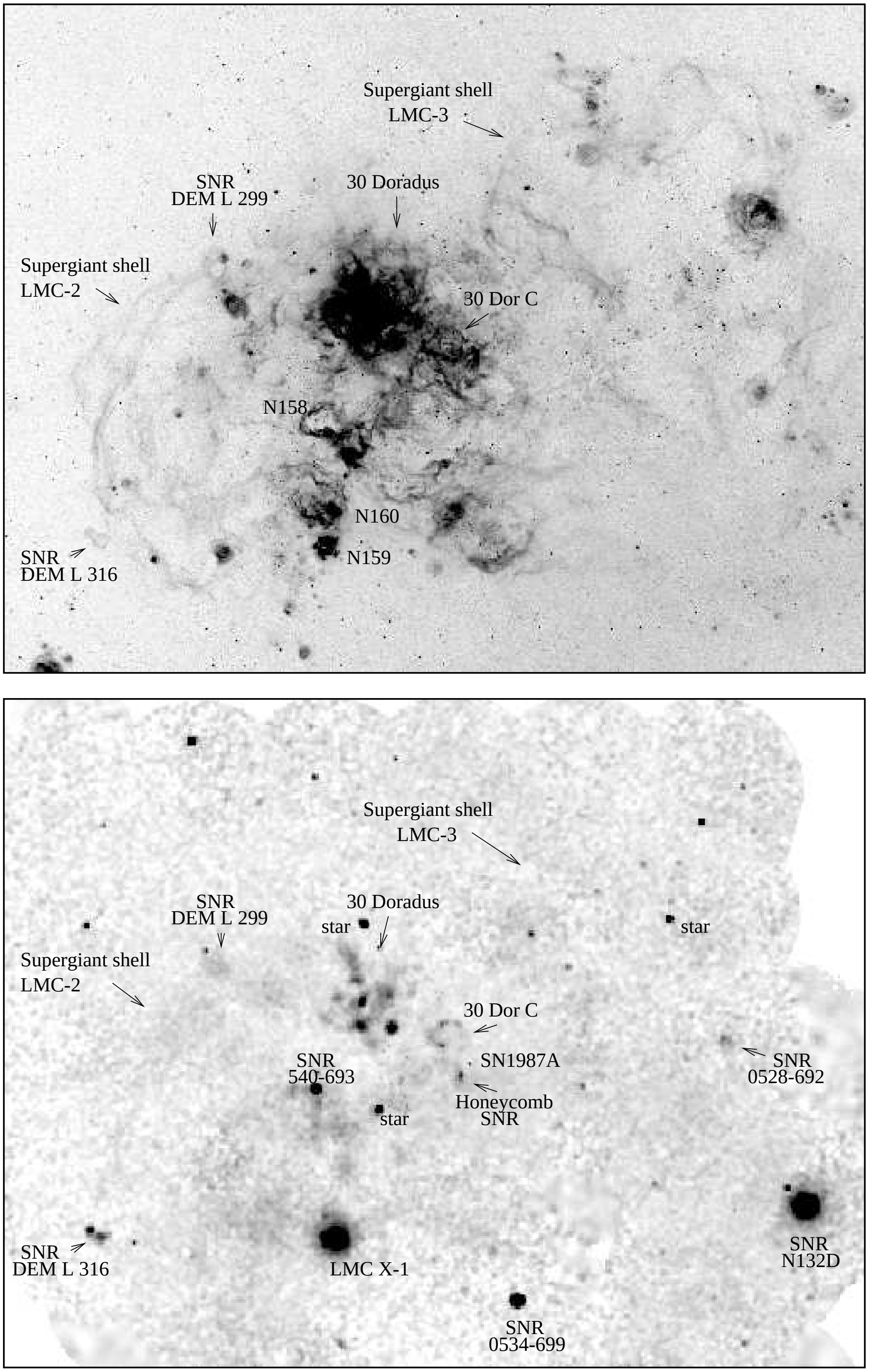

Fig. 5. (*Top*) Hα image of the 30 Dor complex and its vicinity. (*Bottom*) *ROSAT* HRI X-ray mosaic of the same region. The field of view is $140' \times 110'$. Diffuse X-ray emission is clearly detected in SNRs, some superbubbles, the giant H II region 30 Dor, and two supergiant shells.

4. HOT GAS EMBEDDED IN THE DISK

The hot gas confined within superbubbles or giant H II regions is probably in the disk; however, the hot gas in a supergiant shell may extend to large distances from the disk and may blowout into the halo. Some of the diffuse X-ray emission from the LMC does not seem to be confined by cool interstellar shell structures; it is uncertain whether this hot gas is in the disk or in the halo. To determine the vertical distribution of hot gas, it is necessary to use interstellar absorption lines of high ions in the UV, e.g., C IV, N V, and O VI, which exist at the interfaces between 10^4 K gas and 10^6 K gas. Using early-type stars in the disk as probes, it may be possible to determine the position and velocity of the hot gas relative to the cooler gas in the disk.

Hot gas in the halo of the LMC has been unambiguously demonstrated recently by Wakker et al. (1998), using *HST* GHRS spectra of five carefully selected probe stars in the LMC. The probe stars have spectral types of O9–B3 so that they do not photoionize C to C^{+3} in their surrounding medium. They are also selected to be away from large interstellar shell structures to avoid confusion from the hot gas in shell interiors. Interstellar C IV absorption is detected in all five sightlines. Furthermore, the C IV lines are blue-shifted with respect to the Hα line by 25–60 km s^{-1}, indicating that the hot gas is moving away from the cooler gas in the disk. These results strongly suggest that the LMC possesses a patchy hot gas halo.

The *HST* STIS and the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) provide us with exciting opportunities to probe the depth structure of the hot gas in the LMC using the interstellar C IV, N V, and O VI absorption lines. Observations of a large number of probe stars in the LMC are needed to determine the structure of its hot gas halo, and to study the physical conditions of interfaces between 10^4 K and 10^6 K gases.

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