STRUCTURE AND EVOLUTION OF HOT GAS IN 30 DOR

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ABSTRACT

We have investigated the structure and evolution of hot gas in the 30 Dor nebula, based on recent X-ray observations. Our deep ROSAT HRI image shows that diffuse X-ray emission arises in blister-shaped regions outlined by loops of H II gas. X-ray spectroscopic data from ASCA confirm the thermal nature of the emission and indicate that the temperature of the hot gas decreases from the core to the halo of the nebula. The structure of the nebula can be understood as outflows of hot and H II gases from the parent giant molecular cloud of the central OB association. The dynamic mixing between the two gas phases is likely responsible for the mass loading to the hot gas, as required to explain the observed thermal structure and X-ray luminosity of the nebula. Such processes should also be important in the formation of similar giant H II regions and in their subsequent evolution into supergiant bubbles or galactic chimneys.

Subject headings: galaxies: ISM — H II regions — ISM: bubbles — ISM: individual (30 Doradus) — ISM: structure — Magellanic Clouds — X-rays: ISM

1. INTRODUCTION

As the most luminous H II nebula in the Local Group of galaxies, 30 Dor in the Large Magellanic Cloud (LMC) provides the most accessible paradigm to understand massive star formation and its interaction with the interstellar medium. Responsible for the ionization of this spectacular nebula ($\sim 10^{52}$ Ly photon s$^{-1}$) is the OB association NGC 2070. The central cluster R136 ($r \lesssim 10$ pc; assuming the LMC distance as $D = 47$ kpc; Gould 1995) alone accounts for about half of the required ionization radiation (Walborn & Blades 1997; Crowther & Dessart 1998, and references therein). The bulk of very massive stars, contained primarily within the compact core of the cluster ($r \sim 2$ pc), were formed in a star-forming burst about 1–2 Myr ago (Massey & Hunter 1998). H II filaments form shells or loops that often extend more than 100 pc away from the central cluster (e.g., Chu & Kennicutt 1994). However, no model has yet been proposed to explain the origin and evolution of this nebula structure.

The 30 Dor nebula is the first giant H II region shown to be a strong diffuse X-ray emitter. As seen in an IPC image of the Einstein Observatory (Wang & Helfand 1991), the emission peaks within H II shells, indicating the presence of hot gas of a few times $10^6$ K. Stellar winds from massive stars and supernova explosions are presumably responsible for the heating of the gas. Relatively recent observations with the ROSAT Position-Sensitive Proportional Counter (PSPC) have confirmed the Einstein results (Norci & Ogelman 1995; Chu 1993).

In this Letter, we present a study of 30 Dor based chiefly on a deep X-ray image from the ROSAT High-Resolution Imager (RHRI) and on an X-ray spectrum from ASCA. These two complementary data sets enable us to spatially resolve the detailed X-ray emission structure and to characterize the thermal properties of the hot gas. We compare the X-ray data with optical and UV observations and extend our discussion (Wang 1996) about the origin of the hot gas and its subsequent evolution.

2. DESCRIPTION OF THE X-RAY DATA

The RHRI image, as presented in Figure 1, is a co-add of three observations: ROSAT numbers rh600228n00 (30 ks exposure), rh400779n01 (79 ks), and rh400779n00 (26 ks). The first observation has already been used in the study of the two bright pointlike sources in the core of the nebula, which are Wolf-Rayet/black hole binary candidates (Fig. 2; R140 and Mrk 34; Wang 1995), and the Crab-like supernova remnant N157B (Wang & Gotthelf 1998a). The second observation has been utilized for both timing and positioning of the recently discovered 16 ms pulsar within the remnant (Wang & Gotthelf 1998b, and references therein). Briefly, the RHRI data have a spatial resolution ranging from ~6" (FWHM) near the image center to ~30" near the edges, or a factor of up to ~10 (5) better than the resolution of the IPC (PSPC). The energy coverage is in the range of 0.1–2 keV. We processed the RHRI data with a software provided by S. Snowden for data editing, background subtraction, and exposure correction. We then adaptively smoothed the resultant X-ray intensity image with a Gaussian of adjustable size to achieve a uniform signal-to-noise ratio of 6 for Figure 1 and 4 for Figure 2.

The X-ray spectral data were obtained from the ASCA SIS observation number ad20000000. Wang & Gotthelf (1998a) have presented two broadband images constructed from this observation, which had a spatial resolution of ~1' (FWHM) and a spectral resolution of $\delta E/E \sim 0.02(5.9$ keV/E$)^{0.5}$. The observation, taken in a 4 CCD mode, was pointed at R.A., decl. (J2000) = 5$^\circ$38$^\prime$32$^\prime\prime$, $-69^\circ$9$^\prime$44$^\prime\prime$ and had a roll angle of 20.3' north to east. We utilized only the data from the two northern CCD chips of each sensor to minimize the contamination caused by scattered counts from N157B, PSR B0540–69, and LMC X-1 to the south. Specifically, the on-nebula spectrum was extracted from a half circle of 7.5 radius, centered at the pointing direction, plus a northern stretch of 5.4 wide to complete the coverage of the northern X-ray spur of the nebula (Fig. 1). We estimated the background from the same on-nebula chip areas in the adjacent observation (ad90001000 center at $5^\circ$43$^\prime$31$^\prime\prime$, $-69^\circ$13$^\prime$48$^\prime\prime$), just east of 30 Dor. We also tested an alternative background estimate from the regions away from the nebula but in the same on-nebula CCD chips. The resultant background-subtracted spectra are essentially the same; the differences in best-fit spectral parameters (Table 1) are all within 5%. We added the spectra from both sensors of each observation (on- or off-nebula) for subsequent spectral model fitting.
This spectral data reduction followed the procedure prescribed in the on-line ASCA Data Reduction Guide.¹

3. RESULTS

The X-ray emission from 30 Dor is predominantly diffuse in origin. Figure 1 shows no evidence for pointlike X-ray sources that may be related to 30 Dor, except for the two X-ray binary candidates mentioned above (§ 2) and the apparent X-ray contribution from R136 (Fig. 2). In general, there is no detailed correlation between the X-ray emission and the presence of massive stars, as appear in the Astro-1 Ultraviolet Imaging Telescope UV image (Fig. 3; Hill et al. 1993). The detection limit for an individual pointlike source is $\sim 1 \times 10^{38}$ ergs s$^{-1}$ (0.5–2 keV). Enhanced diffuse X-ray emission is enclosed within H α loops, which are typically anchored to dense molecular clouds in the core of the nebula (Wang 1996; Fig. 3). But the detailed morphology of individual features remains uncertain. It is still difficult to disentangle various projection effects and differential X-ray absorption across the field. For example, the two shell-like features of $\sim 3'$ diameters to the south of R136 may well be the projection of two loops that originate in the core of the nebula. Apparently, the 30 Dor nebula is a complex of diffuse X-ray–emitting blisters.

In the central region (Fig. 2), strong X-ray emission arises in cavities outlined by ionization fronts (Scowen et al. 1998) at boundaries of molecular clouds (e.g., Wang 1996; Johansson et al. 1998; Rubio et al. 1998). The cavity around R136, in particular, is a well-defined blister that is open, at least to the east (e.g., Dickel et al. 1994). H α gas kinematics (e.g., Chu & Kennicutt 1994) show that the eastern part of this blister is expanding much more rapidly than the western part. This expansion is most likely driven by X-ray–emitting gas that is flowing out from near R136 to the halo of the nebula. The transition zone between the core and the halo of the nebula appears at $r \sim 2'-4'$ from R136, at outer boundaries of the parent giant molecular cloud (GMC) of the OB association. Particularly in the east-west direction, Hα-emitting filaments clearly show the morphology of outward streamers (Fig. 3).

The ASCA spectral data (Fig. 4) confirm that X-ray emission in the 0.5–2 keV band is predominantly thermal in origin. Emission lines are clearly present: e.g., Ne ($\sim 1.0$ keV), Mg (1.3 keV), and Si (1.9 keV). The flat spectrum at higher energies, however, suggests the presence of a nonthermal component, which may represent the expected hard X-ray spectral tails of the black hole binaries (Wang 1995). A power law with

¹ Available at http://heasarc.gsfc.nasa.gov/docs/asca/abc/abc.html.
Table 1

| Parameters         | Values |
|--------------------|--------|
| Photon Index       | 2 (fixed) |
| Norm               | $3.9 \times 10^{-4}$ |
| Low temperature    | 0.150 (0.145–0.159) keV |
| Norm               | 0.94 |
| High temperature   | 0.81 (0.73–0.89) keV |
| Norm               | $9.7 \times 10^{-3}$ |
| Fe L-shell         | 0.71 (0.62–0.80) keV |
| Gaussian width     | $<9.5 \times 10^{-2}$ keV |
| Ne Line            | 1.03 (0.99–1.06) keV |
| Gaussian width     | $<3.1 \times 10^{-3}$ keV |
| Si Line            | 1.35 (1.34–1.36) keV |
| Gaussian width     | $<2.6 \times 10^{-2}$ keV |
| Column density     | 1.43 (1.35–1.48) $\times 10^{22}$ cm$^{-2}$ |

Note.—The spectral normalizations are in the standard XSPEC units: photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV for the power law and $[10^{-14}/(4\pi D^2)] n_e n_H dV$ for the two thermal plasma components, where $D$ is the distance to 30 Dor, $n_e$ and $n_H$ are the electron and hydrogen densities (all in cgs units). The metal abundances are assumed to be 30% of the solar values for both X-ray-emitting and absorbing gases. The uncertainty intervals are all at the 90% confidence.
fore, the hard temperature component also originates predominately in diffuse hot gas, and its temperature apparently decreases from the core to the halo of the nebula.

The X-ray spectral analysis further provides a measurement of the mean X-ray–absorbing gas column density toward 30 Dor. A comparison of the measured column density $N_{\text{H}}$ (Table 1) with the mean reddening $E(B-V) = 0.4-0.5$ of 30 Dor (e.g., Parker 1993; Dickel et al. 1994) gives $N_{\text{H}}/E(B-V) \approx 3.1 \times 10^{22}$ cm$^{-2}$ mag$^{-1}$, which is considerably greater than $N_{\text{H}}/E(B-V) \approx 2.4 \times 10^{22}$ cm$^{-2}$ mag$^{-1}$ (Fitzpatrick 1986). This is expected because $N_{\text{H}}$ includes contributions from both partially ionized and molecular gas phases, in addition to the H$\text{I}$ column density $N_{\text{H, I}}$. The X-ray absorption in the ASCA energy range ($\approx 0.5$ keV) is insensitive to the ionization and chemical states of the gas (Morrison & McCammon 1983).

Using the best-fit spectral model (Table 1), we estimate physical parameters of hot gas in the nebula. An approximate conversion between the observed RHRI intensity to the emission measure of hot gas is $\approx 40$ cm$^{-6}$ pc (counts ks$^{-1}$ arcmin$^{-2}$)$^{-1}$ with an uncertainty of $\approx 2$ within the ranges of the spectral parameters. The total count rate from a circle of 10$''$ radius

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**Fig. 3.—**Comparison of 30 Dor in H$\alpha$ (green), UV (blue), and X-ray (red).

**Fig. 4.—**ASCA SIS spectrum of 30 Dor. Individual spectral components are plotted separately: power law (dashed line; dominating above 4 keV), the low- (solid line) and high-temperature (dash-dotted line) thermal components, and the three Gaussian emission lines (Table 1).
around R136, excluding the N157B and pointlike source contributions, is \( \sim 0.26 \text{ counts s}^{-1} \). This rate corresponds to an intrinsic luminosity \( L_{\text{X}}(0.5 – 2 \text{ keV}) \sim 9 \times 10^{37} \text{ erg s}^{-1} \) and a radiative cooling rate of \( \sim 1 \times 10^{39} \text{ ergs s}^{-1} \). The spectral parameters of the high- and low-temperature thermal components suggest an average pressure \( p/k \sim 2 \times 10^7 \text{ K cm}^{-3} \) in the core and a factor of \( \sim 7 \) lower in the halo of the nebula. The total thermal energy and mass of the hot gas, if within a sphere of \( r = 140 \text{ pc} \) and with a volume filling factor \( f_{\text{H} \alpha} \) (in units of 20\%), are \( (3 \times 10^{10} \text{ ergs}) f_{\text{H} \alpha} \) and \( (4 \times 10^{31} M_\odot f_{\text{H} \alpha}) \), contained mostly in the low-temperature component.

4. DISCUSSIONS

The formation of the giant 30 Dor nebula is clearly driven by the intense energy release from massive stars. With a total mass-loss rate of \( \sim 10^{-3} M_\odot \text{ yr}^{-1} \) and a typical terminal wind velocity of \( \sim 3 \times 10^3 \text{ km s}^{-1} \), the central cluster R136 alone has a stellar wind luminosity of \( \sim 3 \times 10^{39} \text{ ergs s}^{-1} \) (e.g., Chu & Kennicutt 1994). Over its lifetime, the cluster should have released \( \sim 10^{51} \text{ ergs} \) of mechanical energy. A substantial fraction of this energy is contained in the hot gas, and the radiative cooling of the hot gas is considerable (§ 3). The remaining energy could be accounted for by the global and turbulent motion of various gas components (e.g., Chu & Kennicutt 1994) and by the energy loss to the formation of dense gas shells or filaments (Mac Low & McCray 1988). In comparison, the hot gas in the central cavity accounts for only \( \sim 10^{51} \text{ ergs} \). Thus, outflows must have occurred. Through a highly inhomogeneous and clumpy medium, the outflows can naturally lead to the formation of X-ray-emitting blisters of various shapes and kinematics (Wang 1996).

The key process involved in the evolution of the hot gas is mass loading. Just behind the terminal shock, stellar wind materials have a temperature of \( \sim 10^7 \text{ K} \), which is 1 order of magnitude greater than the measured average temperature of hot gas even in the core of the nebula. The mass loading can naturally increase the density and decrease the temperature of the materials, necessary for explaining the observed X-ray emission.

The most effective mass-loading process is likely the dynamic mixing of hot gas with H \( \text{II} \) gas. While the mass efficiency of massive star formation is typically only 5%–10% (e.g., McKee 1989), much of the parent GMC of the OB association is being eroded via photon evaporation. The erosion has been accelerated greatly since the nebula broke out from the GMC. The mass eroding rate can be estimated as (Whitworth 1979; York et al. 1989) \( \sim 0.12 M_\odot \text{ yr}^{-1} \left( \frac{L_{\text{X}}}{10^{25} \text{ Ly photons s}^{-1}} \right) \left( \frac{t_{\ast}}{10^6 \text{ yr}} \right)^{1/2} \left( \frac{M_{\ast}}{M_\odot} \right)^{1/2} \), where \( S_\ast \), \( t_\ast \), and \( M_{\ast} \) are the ionizing flux of NGC 2070, the effective age of the OB association with the present flux, and the mean density of the GMC. Only if \( \sim 10\% \) of this photon-evaporated H \( \text{II} \) gas is loaded to the shocked wind materials in the core of the nebula can the temperature of hot gas there be explained. Over the lifetime of the nebula, the total evaporated mass is \( \sim 10^4 M_\odot \). In order to account for the total mass of hot gas (\( \sim 4 \times 10^4 M_\odot \)), the mass loading over the nebula must be substantial.

The dynamic mixing is evident, right within the central cavity around R136, Hubble Space Telescope Wide Field Planetary Camera 2 images of optical emission lines clearly demonstrate the presence of evaporative flows from various ionization fronts into the interior of the cavity (Scowen et al. 1998). Such flows are caused by the lack of a pressure confinement of H \( \text{II} \) gas after hot gas has largely escaped from the GMC through outflows. Both the interaction between stellar winds and evaporative flows and the interface between the outflows of hot and H \( \text{II} \) gases are highly unstable. The dynamic mixing can naturally occur.

Supernova explosions may also play a role in the formation of the 30 Dor nebula. To be energetically important, however, the number of explosions needs to be several tens, at least, if each releases typically a few times \( 10^{50} \text{ ergs} \) of mechanical energy. Supernova blast waves can sporadically shock large amounts of evaporated H \( \text{II} \) gas in the core. The relatively high pressure there tends to drive the heated gas out into the halo of the nebula, similar to the outflows of mass-loaded stellar wind materials.

This study of 30 Dor leads us to conclude that outflows of giant H \( \text{II} \) regions (GHRs) from GMCs can naturally convert large amounts of molecular gas into hot gas via photon evaporation, dynamic mixing, and occasionally shock heating. Such mass loading can greatly enhance the radiative cooling of the hot gas, and therefore the X-ray luminosities of the GHRs. The hot gas properties of supergiant bubbles and galactic chimneys can also be affected, since they are all evolved from GHRs and have most likely experienced the outflow phase.

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