Research Progress on the Large Magellanic Cloud Superbubble 30 Doradus C: A Postprint

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Abstract

Superbubbles are giant shell-type bubble-like interstellar medium structures driven by stellar winds from massive stars and/or supernova explosions in OB associations, exhibiting prominent emission features across multiple wavebands and serving as important sites for studying astrophysical radiation mechanisms. 30 Dor C is the only superbubble in the Large Magellanic Cloud observed to exhibit significant non-thermal radiation, which covers the entire superbubble region and is most prominent at the shell, making it the largest extended non-thermal radiation source in the Large Magellanic Cloud. This paper reviews and summarizes the research findings on 30 Dor C to date within the astronomical community, introduces the basic properties of extended sources within the superbubble—including X-ray thermal radiation, non-thermal radiation, and results from other wavebands—while also compiling information on discovered point sources within the superbubble, and discusses key issues such as evidence for particle acceleration within the 30 Dor C superbubble, possible particle acceleration mechanisms, and the origin of the superbubble.

Full Text

Preamble

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Current Investigation on Superbubble 30 Doradus C in the Large Magellanic Cloud

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Abstract

Superbubbles are large shell-like interstellar medium structures formed by stellar winds from massive stars and supernovae, exhibiting obvious emission signatures across multiple wavelengths that make them important sites for studying radiation mechanisms. 30 Doradus C (30 Dor C) is located southwest of 30 Dor in the Large Magellanic Cloud, with its position basically consistent with OB association LH 90, suggesting that this superbubble may have been created by it. Since 30 Dor C was detected in the X-ray band by the Einstein satellite in 1981, its X-ray emission has been observed and studied for many years. 30 Dor C is the only superbubble dominated by non-thermal emission in the Large Magellanic Cloud and is also the largest non-thermal X-ray emission source in the Local Group. The non-thermal emission covers the entire region of the superbubble and is most significant at the shell. Such bright non-thermal emission may be due to particle acceleration in the superbubble, and to investigate this evidence, the magnetic field conditions in the superbubble and radiation in other bands have also been studied. Compared to non-thermal emission, thermal emission in 30 Dor C is relatively faint, with most thermal emission detected in the eastern region. Additionally, a supernova remnant has been found outside the superbubble at the southeast of the shell. In recent years, with the advancement of radio observations, studies of molecular clouds in 30 Dor C have also increased. This paper reviews and summarizes the research on 30 Dor C to date, discussing the basic situation of thermal emission, non-thermal emission, and other bands, while providing a summary of the point sources discovered inside the superbubble. We discuss the evidence for particle acceleration inside 30 Dor C according to the radiation characteristics, as well as current particle acceleration models and the formation mechanisms of 30 Dor C.

Keywords: superbubble; Large Magellanic Cloud; ISM

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1 Introduction

Superbubbles are large shell-like structures composed of interstellar medium (ISM), with diameters typically ranging from 100 to 1000 pc [1]. Their interiors are filled with shock-heated gas at high temperatures (10^6 K) [2], and they are driven by stellar winds from massive stars in OB associations and/or supernova explosions [3]. The intense stellar winds from massive stars or shocks from supernovae compress their ejecta and the surrounding ISM, forming a thin, dense, cool outer shell. According to supernova theory, shocks begin to decelerate when the ejected material becomes comparable to the swept-up ambient material. Because the ISM density inside superbubbles (on the order of 0.01 cm^{-3}) [4] is much lower than that of the external environment (1 cm^{-3}), the timescale for effective particle acceleration is longer than in isolated supernova remnants. Additionally, since both massive stellar winds and supernovae contribute to the total energy of the superbubble, the energy stored in superbubbles is greater than in individual supernova remnants [1], making them potential sources of high-energy cosmic rays at TeV energies and beyond [5, 6].

The Large Magellanic Cloud (LMC) offers excellent observational conditions, with a moderate distance (approximately 50 kpc) [7], a low inclination angle nearly face-on (approximately 35°) [8], and low foreground absorption ($A_v < 0.3$ mag) [9]. Furthermore, as an SB(m)-type galaxy, the LMC provides numerous high-energy astrophysical objects such as supernova remnants, superbubbles, and pulsar wind nebulae, making it an ideal laboratory for studying various celestial objects and their physical mechanisms.

30 Doradus C (hereafter 30 Dor C) [Figure 1: see original paper] is located in the southwestern part of the 30 Dor complex in the LMC, approximately 200 pc from the massive star-forming region R136. To its east lies the supernova remnant N157B, to the southwest is SN 1987A, and to the south is the Honeycomb Nebula. Moreover, the position of 30 Dor C coincides with the large OB association LH 90 (NGC 2044), which consists of multiple star clusters containing several Wolf-Rayet stars [10]. Therefore, 30 Dor C may have been generated by the stellar winds and supernovae within LH 90 [11]. 30 Dor C was first discovered through radio continuum observations by Le Marne in 1968 [12], and Mills et al. (1984) detected a shell diameter of approximately 6’ at 843 MHz, corresponding to about 80 pc at the LMC distance of ~50 kpc [13, 14]. The Einstein satellite first observed X-ray emission from 30 Dor C [15], and ROSAT subsequently detected its shell-like structure [16]. In 2000, XMM-Newton’ s initial imaging covered the 30 Dor C region, revealing a similar shell structure in both thermal and non-thermal X-ray emission [17].

Non-thermal X-ray radiation provides the best evidence for identifying sites of cosmic-ray acceleration. To date, non-thermal emission has been detected in only a handful of superbubbles, both within the Galaxy (e.g., RCW 38 [18], Westerlund 1 [19]) and in the LMC (N11 [20], N51D [21], 30 Dor C [22–25]), as well as IC 131 in M33 [26] (although the non-thermal nature of N11 and N51D remains uncertain [27]). Among these Local Group superbubbles, 30 Dor C possesses the brightest non-thermal X-ray and TeV γ-ray emission [28]. Consequently, comprehensive observations and studies of 30 Dor C will significantly advance our understanding of superbubble physical properties and particle acceleration mechanisms.

In this paper, we first review the diffuse emission across various wavelength bands and the point sources within 30 Dor C, then summarize studies of molecular clouds in the region, and finally provide a synthesis and outlook for future research.

2 Radiation Properties

Studies of 30 Dor C' s emission have primarily focused on the X-ray band, where the superbubble' s shell structure exhibits regional variations. The Chandra X-ray Observatory [22, 25, 30, 31], XMM-Newton telescope [23, 25, 32], and Suzaku [24] have provided rich X-ray datasets for 30 Dor C. Additionally, the superbubble has been observed and studied in optical (e.g., MCELS [33]), radio (e.g., ALMA [28]), and γ-ray bands (e.g., H.E.S.S. [34]).

2.1 X-ray Thermal Emission

Superbubbles form through the combined action of massive stellar winds and core-collapse supernova explosions. High-velocity winds from massive stars, particularly during the Wolf-Rayet phase of late evolution, together with supernova explosions, generate strong shocks and X-ray radiation. This X-ray emission can be divided into two categories based on radiation mechanisms: thermal and non-thermal. When strong shocks heat the gas within the superbubble to temperatures of $10^6 - 10^7$ K, the gas radiates X-rays accompanied by emission lines from He-like and H-like ions of intermediate-mass elements such as O, Ne, and Mg. Wolf-Rayet star winds are enriched in elements like C and N, while supernova ejecta contain high abundances of intermediate-mass elements. When these metal-rich materials are shock-heated, their X-ray spectra exhibit exceptionally strong emission lines from intermediate-mass elements, which can be used to infer the properties of supernova progenitors [29]. Shocks accelerate relativistic electrons through mechanisms such as Fermi acceleration to energies exceeding 10^{13} eV, producing X-ray synchrotron radiation. The synchrotron spectrum follows a simple power law, differing from thermal radiation spectra in two key aspects: first, the non-thermal power-law spectrum is remarkably smooth and lacks any emission line features; second, its flux decays more slowly with frequency, typically resulting in a harder spectrum that dominates above 2 keV. These characteristics facilitate the distinction between thermal and non-thermal X-ray emission in superbubbles.

Overall, 30 Dor C is dominated by non-thermal emission, with thermal emission primarily appearing in the eastern region. Bamba et al. [30] performed spectral analysis of the eastern part of the superbubble and found that the northeastern shell' s spectrum differs from the purely non-thermal component seen in the western shell; its spectrum appears softer and cannot be fitted with a single model. The brightest and most prominent thermal emission in the entire superbubble occurs in the southeastern region. Kavanagh et al. [25] confirmed that this bright thermal emission is associated with a supernova remnant, MCSNR J0536-6913, though no clear optical or radio emission related to this remnant was detected. Since no evidence of interaction between the supernova explosion and the superbubble shell has been observed, and the X-ray emission from the remnant appears brighter in the north—indicating higher ambient density there than in the south—the remnant is likely located outside the superbubble, as the low-density interior of the superbubble cannot produce such a bright, compact shell structure. The remnant contains ejecta composed of O, Ne, Mg, and Si elements. Based on the abundance ratios of these ejecta and comparison with supernova explosion models, the progenitor star likely had a mass of 18 $M_{\odot}$ or ≥ 40 $M_{\odot}$. Based on this progenitor mass range, the remnant' s age is estimated to be $(2.2-4.9)\times10^3$ yr.

Thermal emission is primarily detected in the eastern region. One possible explanation is that a nearby supernova explosion is interacting with the shell wall. Additionally, higher ambient density could also produce this phenomenon, as thermal emission intensity is proportional to the square of density. After subtracting the contribution from the southeastern supernova remnant, traces of thermal emission remain in the eastern part of the superbubble, with overabundances of O, Ne, and Mg elements. This suggests recent interaction between a core-collapse supernova and the superbubble shell [25]. Furthermore, high metallicity can enhance X-ray luminosity in this region [35]. The temperature of the thermal plasma varies slightly across regions, generally falling within the range $kT_e = 0.17-0.86$ keV. Since 2002, thermal components have been detected in the eastern part of 30 Dor C using observations from Chandra, XMM-Newton, Suzaku, NuSTAR, and other instruments (see Table 1). Babazaki et al. [32] performed a detailed analysis of 30 Dor C covering the entire region at a scale of approximately 10 pc, finding thermal components in most of the eastern half of the superbubble while detecting almost none in the western half.

Table 1 Thermal component fitting results for the eastern region of 30 Dor C

Southeast (SNR subtracted) kT_e/keV: 0.19(0.17-0.23), 0.21(0.19-0.23), 0.66(0.58-0.76), 0.28(0.20-0.34), 0.31(0.28-0.34), 0.40(0.37-0.46), 0.18(0.17-0.19), 0.86(0.85-0.87)

Note: Numbers outside parentheses represent best-fit values; numbers inside parentheses indicate 90% confidence intervals.

The western region of the superbubble is dominated by bright non-thermal emission. Contrary to previous results, Lopez et al. [4] found that a thermal component with temperature $kT = (0.86 \pm 0.01)$ keV is required in the southwestern part of the superbubble. Using recent eROSITA data, Sasaki et al. [36] performed spectral fitting of the western region and obtained a thermal component of 0.62(0.28-1.1) keV, which they considered consistent with Lopez' s result. However, the two studies analyzed different regions with different background selections, leaving the reality of this western thermal component still uncertain.

Currently, thermal emission has not been definitively detected in other regions. The non-detection of thermal emission from the northwestern shell may be due to high foreground molecular cloud absorption column density and the dominance of bright non-thermal emission in that region’ s spectrum, making it difficult to identify thermal components. In the inner part of the northeastern shell, where absorption is lower than in the northwestern shell, Kavanagh et al. [25] suggested that a potential thermal component may exist. In summary, the identification and parameter constraints of thermal components in 30 Dor C remain controversial and require further investigation.

2.2 X-ray Non-thermal Emission

Since synchrotron X-rays were discovered in the shell of SN 1006 [37], several Galactic supernova remnants have been identified as acceleration sites for high-energy cosmic rays. 30 Dor C is the first extragalactic source analogous to SN 1006, and at the time of its discovery, its non-thermal luminosity was the brightest among all known synchrotron-emitting sources [30]. The total non-thermal luminosity is approximately 5.3×10^{28} J s^{-1} [22], marking the first detection of non-thermal radiation from a superbubble shell. Non-thermal X-ray emission is not confined to the shell but distributed throughout the entire superbubble region, indicating that the bright shell is a projection effect. Across the shell, non-thermal emission in the west is generally brighter than in the east, with the northwestern shell being the brightest region. Over the past two decades, numerous studies have investigated the non-thermal emission from the superbubble. Bamba et al. [22] fitted the shell spectrum with an excellent power law, obtaining photon indices in the range 2.1–2.9. Kavanagh et al. [25] conducted a spectral analysis covering the entire superbubble, deriving power-law indices of 2.29–2.88. Subsequent work in 2019 found indices of 2.20–2.70 in some regions [31]. Babazaki et al. [32] performed a highly detailed segmentation of the superbubble, with final photon indices also falling primarily between 2 and 3. These fitting results all indicate typical synchrotron radiation.

The radio shell at 843 MHz shows a high degree of correlation with the non-thermal X-ray distribution [22], with non-thermal X-rays enhanced at locations of bright radio emission, indicating that the radiation mechanisms are consistent across these bands. The presence of radio polarization [25] further supports the interpretation that non-thermal X-rays likely originate from synchrotron radiation of accelerated electrons [22]. Nakamura et al. [38] discussed the time evolution of non-thermal components as a function of radius in supernova remnants, which can serve as an indicator of the dynamical age described by Weaver et al. [39]. Drawing an analogy to this, Babazaki et al. [32] investigated the relationship between non-thermal luminosity and superbubble radius for several non-thermal-emitting superbubbles. They found that 30 Dor C lies near the peak, at a radius of approximately 40 pc, indicating that 30 Dor C is in a high-energy particle acceleration phase and thus exhibits bright synchrotron X-ray emission [32]. This also implies that the duration of high-energy electron acceleration can far exceed the previously accepted consensus for supernova remnants (approximately 10^3 yr [40]). The extended electron acceleration timescale and the remarkable non-thermal emission intensity may be attributed to several supernova explosions occurring within the superbubble over millions of years, continuously supplying high-energy electrons.

Under the assumption that multiple supernovae have exploded within the superbubble, particle acceleration in 30 Dor C differs from that in single, isolated supernova remnants. Parizot et al. [41] demonstrated that massive stars in OB associations are sufficiently close for their winds to interact, generating strong turbulence and magnetohydrodynamic (MHD) waves that can repeatedly accelerate low-energy particles. Considering various mechanisms within superbubbles, they found that repeated acceleration can produce particles with energies up to approximately 10^{17} eV. Approximately 10%-30% of the turbulent energy in superbubbles can be transferred to low-energy non-thermal particles to accelerate them [42], while up to one-third of the energy from stellar winds and supernovae can be used for cosmic-ray acceleration [43]. Lopez et al. [4] showed that the mechanical energy from the stellar population and previous supernova explosions within the superbubble is sufficient to explain the observed non-thermal flux.

2.3 Emission in Other Bands

2.3.1 γ-ray Band Studies H.E.S.S. announced the detection of TeV γ-rays from 30 Dor C in 2015 [34]. Subsequent Fermi-LAT observations did not definitively detect an extended GeV γ-ray source from 30 Dor C [44]. The γ-ray spectrum of 30 Dor C in the 1-10 TeV range can be described by a power law with a luminosity of $(0.9 \pm 0.2) \times 10^{28}$ J s^{-1} [34]. The best-fit location of the γ-ray emission coincides with six identified sub-clusters [10, 34].

γ-ray detection results indicate that conditions within the superbubble must be extreme. The TeV emission can be explained by either hadronic or leptonic scenarios. In the hadronic scenario, hadronic cosmic rays collide with background plasma to produce neutral π^0 mesons, which subsequently decay into γ-ray photons. Based on the TeV luminosity, the relationship between the total energy of cosmic-ray protons and the matter density inside the superbubble can be estimated as $W_{pp} = (0.1 - 25) \times 10^{45} (n_H/1\text{cm}^{-3})^{-1}$ J. Since approximately five supernovae have exploded in 30 Dor C [23], and the cosmic-ray acceleration efficiency from supernova explosion kinetic energy is roughly 5%-20% [45], the energy available for cosmic rays is about 5×10^{43} J. This yields an average gas density of $n_H \gtrsim 20$ cm^{-3}, which is significantly higher than the value of $n_H \approx 0.1 - 0.4$ cm^{-3} estimated from X-ray thermal emission in the southwestern part of the superbubble [34]. If the radius of the X-ray thermal emission is smaller than that of the dense outer shell, or if cooled, dense clumpy gas can survive in the tenuous interior of the superbubble, then high-density regions could exist.

For the leptonic scenario, γ-rays originate from bremsstrahlung and inverse Compton scattering of electrons–the same electron population responsible for X-ray synchrotron radiation. In this case, the energy required for accelerated electrons in the broadband spectral energy distribution is approximately 4×10^{41} J, with an average magnetic field strength of 1.5×10^{-12} T. This is lower than in most young supernova remnants but 3–4 times higher than the average magnetic field in the LMC [34]. At high energies, bremsstrahlung contributions become negligible [46], and since the X-rays are non-thermal, the emission can be explained by the propagation of high-energy electrons into dense molecular clouds with enhanced magnetic fields [47].

[Figure 2: see original paper] shows the spectral energy distribution of 30 Dor C with hadronic and leptonic models, combining X-ray, GeV, and TeV observations and using Fermi-LAT spectral flux as an upper limit to discuss the nature of this TeV source. In the leptonic scenario, the derived magnetic field of the radiation field is $(1.0-1.8)\times10^{-12}$ T [34]. Currently, it is impossible to confirm whether hadronic or leptonic radiation dominates. In 2019, Kavanagh et al. [31] estimated the downstream magnetic field of 30 Dor C from the synchrotron X-ray shell and found generally low downstream magnetic fields, roughly $\gtrsim 2\times10^{-12}$ T. Based on this result, they argued that TeV radiation is dominated by inverse Compton scattering, i.e., the leptonic mechanism is the primary source of TeV γ-rays.

2.3.2 Optical and Radio Emission

The optical and radio emission from the shell of 30 Dor C likely originates from the stellar winds and supernova explosions of the OB association LH 90 (or NGC 2044) [11], which contains 26 O-type stars and 7 Wolf-Rayet stars with ages of approximately 3–7 Myr [10]. Morphologically, the Hα shell of 30 Dor C is well-defined, confining the thermal emission in the eastern part of the superbubble (see Figure 3a [Figure 3: see original paper]) and showing good correlation with the non-thermal X-ray shell (see Figure 3c). The 20 cm radio emission also closely follows the Hα shell morphology, consistent with the standard picture of a superbubble.

The structure appears as a shell-like source in the optical band, with an elliptical shape covering an area of approximately 125 pc × 100 pc. NGC 2044 is also projected within the shell boundary, with the three brightest star clusters distributed roughly along the ellipse' s major axis. Mathewson et al. [48] analyzed the [S II]/Hα ratio, finding values less than 0.3 around the superbubble periphery. Since the [S II] line is shock-sensitive, ratios greater than 0.4 typically indicate possible supernova remnants [49, 50]. Kavanagh et al. [25] reanalyzed the optical emission lines using MCELS data, obtaining results consistent with Mathewson' s original findings (shown in Figure 4a) [48]. In 30 Dor C, the expansion velocity of the Hα shell is less than approximately 100 km s^{-1} [16, 31], whereas in typical supernova remnants, relativistic electrons are thought to be accelerated via diffusive shock acceleration (DSA) [51], requiring shock velocities greater than approximately 1,000 km s^{-1} to achieve TeV energies. Kavanagh et al. [31] demonstrated that shocks stall upon reaching the Hα shell region and expand more rapidly through gaps in the shell. This explanation is consistent with the anti-correlation between Hα and X-rays found in the northeastern and northwestern regions of the superbubble.

Mills et al. [13] began systematic observations of the LMC at 843 MHz using the MOST telescope in 1984, and Mathewson et al. [48] conducted detailed analyses of these radio sources, including 30 Dor C. They found that the spectrum in the western part is flatter than in the eastern part, suggesting that radio emission in the western region is thermal, while the eastern region exhibits both thermal and non-thermal components. McGee et al. [52] corroborated this conclusion, noting that the Hα line intensity is 5% of the continuum in the western shell, clearly indicating a thermal origin. Kavanagh et al. [31] provided a clear analysis of the differences in radio emission between the eastern and western parts of the superbubble (see Figure 4b [Figure 4: see original paper]). The western shell' s spectrum (with index 0.5 $> \alpha >$ -0.5) is remarkably flat, which they interpret as contamination by foreground molecular clouds toward the western part of 30 Dor C. The eastern shell' s spectrum (with index -0.6 $> \alpha >$ -2.2) is significantly steeper. Although the [S II]/Hα ratio is only 0.3, both the optical and radio emission characteristics indicate the presence of a supernova remnant, which was subsequently confirmed in the southeastern part of the superbubble [25].

3 Point Sources

Images across various wavelengths reveal that 30 Dor C exhibits clear multi-point source characteristics. Investigating the properties and origins of these point sources aids in understanding the physical properties of the superbubble. To date, 13 point sources in 30 Dor C have been mentioned in relevant studies. Lortet and Testor [53] studied 30 Dor C in the optical band in 1984, with infrared comparisons, identifying three prominent point sources in the bright central region (sources 6, 10, and 11 in Figure 5 [Figure 5: see original paper]). The spectrum of source 6 indicates it contains a red giant and a Wolf-Rayet star. The brightest star in source 10 is Brey 65, which Moffat [54] classified as WN7 in 1989. Testor et al. [10] reobserved the two compact clusters in the LH 90 region (sources 6 and 10) in 1993, noting that the red supergiant in the cluster represented by source 6 has luminosity comparable to the Wolf-Rayet stars Brey 58 and TSWR 4 located in the same cluster, and suggesting that BAT99 80 may be the optical counterpart of source 10.

Bamba et al. [22] conducted hard X-ray spectral analysis of 30 Dor C in 2004 using the Chandra X-ray Observatory and XMM-Newton telescope. In their point source analysis, they utilized Chandra' s high angular resolution to identify six point sources. Source 6 is the brightest, with a spectrum consistent with a thin thermal plasma model at approximately 2.1 keV, matching X-ray spectra from massive stars and most likely associated with MG 41 and Brey 58. Source 10 has a best-fit photon index of approximately 2, and combined luminosity and spectral analysis suggests it may be a compact object left by a supernova explosion in an active cluster. Source 11 includes an OB star with a soft spectrum consistent with a thermal plasma model, similar to source 6. The other three sources (1, 7, and 12) have hard spectra with no optical counterparts or SIMBAD entries, leading to the suggestion that they may be background AGN or compact remnants of supernova explosions (such as black holes and neutron stars).

Kavanagh et al. [31] processed Chandra X-ray Observatory data in 2019, identifying 10 point sources in the 0.5–0.8 keV image (sources 1–7 and 9–11 in Figure 5). The Lopez team [4] compared NuSTAR X-ray telescope images in the 3–20 keV band with Chandra X-ray Observatory images of 30 Dor C in the 0.5–7.0 keV band in 2020, marking nine point sources (sources 1, 6, 7, 8, and 9–13 in Figure 5). According to the classification by Lin et al. [55] in 2012, source 13 was identified as a candidate compact object binary. The three central point sources in the Chandra X-ray Observatory image (sources 9–11) were not detected by NuSTAR.

4 Molecular Clouds

30 Dor C is considered a site of shock interaction with the surrounding medium, and associated molecular gas clouds have been discovered. Shock-cloud interaction, the so-called "shock-cloud interaction," is an important mechanism for cosmic-ray acceleration and the origin of high-energy emission within Galactic supernova remnants. Shock-cloud interaction enhances turbulence and magnetic fields around gas clouds, producing bright synchrotron X-rays and cosmic-ray electrons with high roll-off energies at the edges [56–58]. Additionally, the surrounding interstellar gas serves as a target for cosmic-ray protons to produce γ-rays through neutral pion decay [59–62].

Sano et al. [46] used ^{12}CO($J = 1-0$) data from the Mopra 22 m radio telescope and ATCA and Parkes HI data to confirm the presence of molecular and atomic gas associated with 30 Dor C. In the superbubble, non-thermal X-ray peaks show good spatial correspondence with molecular clouds. According to their conclusions, most molecular clouds are distributed in the western shell of the superbubble, with a spatial separation of approximately 10 pc between CO emission peaks and synchrotron X-ray peaks. They argued that this spatial separation is not caused by molecular absorption but can be explained by magnetic field amplification around dense clouds through shock-molecular cloud interaction [63, 64]. Yamane et al. [28] obtained higher-resolution results using ALMA ^{12}CO($J = 1-0$), ASTE ^{12}CO($J = 3-2$), and ATCA HI line observations, identifying 23 CO clouds with radii between 3 and 6 pc. They integrated CO and HI data to derive the total proton column density $N_p(\mathrm{H_2} + \mathrm{HI})$ (see Figure 6 [Figure 6: see original paper]), calculated as [28, 65]:

$$N_p(\mathrm{H_2}+\mathrm{HI}) = 2N_p(\mathrm{H_2})+N_p(\mathrm{HI}); N_p(\mathrm{H_2}) = 7.0\times10^{20}W(\mathrm{CO}); N_p(\mathrm{HI}) = 1.823\times10^{18}W(\mathrm{HI})\times X;$$

where $N_p(\mathrm{H_2})$ is the molecular column density, $N_p(\mathrm{HI})$ is the neutral hydrogen column density (both in cm^{-2}), $W(\mathrm{CO})$ and $W(\mathrm{HI})$ are the integrated intensities of CO and HI, respectively, and X is a scaling factor.

Comparison of the spatial distribution of atomic and molecular clouds with X-ray emission reveals that the eastern part of the superbubble, where thermal X-ray emission is brighter, lacks CO/HI clouds, while the western part contains CO/HI clouds but shows no evidence of thermal emission [46]. In contrast to thermal emission, non-thermal X-ray radiation around molecular clouds is significantly enhanced on parsec scales, indicating a positive correlation between molecular/atomic clouds and synchrotron X-ray emission [46]. Yamane et al. [28] compared the ISM distribution with the spatial distribution of X-ray photon indices, absorption column densities, and synchrotron X-ray intensity obtained by Babazaki et al. [32] (see Figure 6). They found that where the total proton column density $N_p(\mathrm{H_2}+\mathrm{HI})$ is high, X-ray emission is stronger, the X-ray photon index is smaller, and scattering is greater, consistent with the interpretation that shock-molecular cloud interaction produces higher-energy cosmic-ray electrons. The X-ray photon index shows an overall decreasing trend toward the centers of massive star clusters, indicating that massive star clusters produce cosmic-ray electrons through supernovae, and thus one or more supernovae may have exploded inside the superbubble [28].

5 Summary and Outlook

This paper has discussed the multi-wavelength emission from superbubble 30 Dor C, including X-ray, optical, radio, and γ-ray bands, as well as studies of point sources and molecular clouds in the region.

In 30 Dor C, non-thermal X-ray emission covers the entire region, while thermal emission is mainly distributed in the eastern part of the superbubble. Fitting results for thermal components are primarily in the range 0.2–0.9 keV. Kavanagh et al. found that the thermal emission in the southeastern part originates mainly from a supernova remnant, MCSNR J0536-6913, located outside the superbubble. Additionally, Lopez et al. and Sasaki et al. both found traces of thermal emission in the western part of the superbubble, a result not mentioned in previous studies, making further investigation of western thermal emission worthwhile. However, due to foreground absorption, existing data cannot well constrain the thermal components.

The non-thermal X-ray radiation in 30 Dor C originates from synchrotron radiation produced by relativistic high-energy particle acceleration. The non-thermal X-ray shell shows good correlation with both the Hα shell and radio shell. γ-ray data have revealed TeV emission from 30 Dor C, consistent with a power-law model. The TeV radiation can be explained by both hadronic and leptonic models, and it is currently impossible to determine which scenario applies, though Kavanagh et al. suggest it may be lepton-dominated.

Yamane et al. argue that synchrotron X-rays result from shock-cloud interactions in the western shell, where abundant interstellar medium amplifies the downstream magnetic field. Past results have shown that more than one supernova has exploded inside the superbubble, providing enormous energy that enables electrons to be accelerated to TeV energies.

Research on 30 Dor C has progressed with the development of observational facilities. Since its discovery by the ROSAT telescope, the primary X-ray data have come from the Chandra X-ray Observatory and XMM-Newton telescope. Due to its unique property of strong non-thermal radiation, the NuSTAR telescope, dedicated to hard X-ray studies, has observed it multiple times. In the emerging field of X-ray polarimetry (e.g., IXPE, eXTP), 30 Dor C will be an important target that may reveal the nature of its non-thermal radiation and cosmic-ray acceleration mechanisms. In the next decade, as X-ray astronomy enters the era of high spectral resolution (XRISM, HUBS, Athena, Lynx, etc.), in-depth studies of the thermal emission components of 30 Dor C will provide material for investigating interactions between massive stellar winds and supernova shocks. In summary, future advances in astronomical technology will enable deeper understanding of this remarkable object, 30 Dor C.

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