A DEEP CHANDRA OBSERVATION OF THE GIANT H\textsc{ii} REGION N11. I. X-RAY SOURCES IN THE FIELD

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ABSTRACT

A very sensitive X-ray investigation of the giant H\textsc{ii} region N11 in the Large Magellanic Cloud was performed using the Chandra X-ray Observatory. The 300 ks observation reveals X-ray sources with luminosities down to \(10^{32}\) erg s\(^{-1}\), increasing the number of known point sources in the field by more than a factor of five. Among these detections are 13 massive stars (3 compact groups of massive stars, 9 O stars, and one early B star) with log\((L_X/L_{\text{BOL}})\) \(\sim -6.5\) to \(-7\), which may suggest that they are highly magnetic or colliding-wind systems. On the other hand, the stacked signal for regions corresponding to undetected O stars yields log\((L_X/L_{\text{BOL}})\) \(\sim -7.3\), i.e., an emission level comparable to similar Galactic stars despite the lower metallicity. Other point sources coincide with 11 foreground stars, 6 late-B/A stars in N11, and many background objects. This observation also uncovers the extent and detailed spatial properties of the soft, diffuse emission regions, but the presence of some hotter plasma in their spectra suggests contamination by the unresolved stellar population.

Key words: galaxies: star clusters: general – ISM: individual objects (LMC N11) – Magellanic Clouds – X-rays: stars

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

With the decade-long work of the sensitive X-ray observatories XMM-Newton and Chandra, a refined picture of stellar X-ray emission in our Galaxy is now available (for a review, see, e.g., Güdel & Nazé 2009). However, many X-ray production processes in stars depend on metallicity, and this dependence has not yet been thoroughly tested. In this context, the Magellanic Clouds provide an opportunity to observe emission effects. For example, the tentative discovery of X-ray emission from low-mass pre-main-sequence (PMS) objects in the Small Magellanic Cloud (SMC) was reported recently and the emission level appears comparable to that in the Galaxy, constraining emission models (Oskinova et al. 2013). On the high-mass end, a 26 ks Chandra exposure of the emblematic H\textsc{ii} region 30 Doradus was reported by Townsley et al. (2006a, 2006b), leading to the detection of 180 X-ray sources—100 being found in the massive central cluster R136, with some of these sources displaying \(\sim 2\) net counts and thus having a non-negligible probability of being spurious. From their spectral analyses, Townsley et al. (2006a) derived absorption columns of \(\sim 10 \times 10^{21}\) H-atom cm\(^{-2}\) for the massive stars of 30 Dor, temperatures of 0.5–4 keV, and absorption-corrected X-ray luminosities from 2 \(\times 10^{33}\) erg s\(^{-1}\) down to \(10^{33}\) erg s\(^{-1}\) (the sensitivity limit). Townsley et al. (2006a) suggested that many, but not all, of the detected massive stars were colliding-wind binaries, which could be ascertained through further monitoring. Furthermore, these authors found no clear \(L_X/L_{\text{BOL}}\) ratio for their sample, contrary to the case for the Galaxy (\(\sim 10^{-7}\), see, e.g., Nazé 2009, and references therein). This conclusion may be reconsidered, however, because (1) significant contamination by X-ray bright colliding-wind binaries (especially WR+O) may hide trends intrinsic to individual massive stars (but correcting this problem requires extensive monitoring in both the optical and X-ray domains, which is not available) and (2) coherent \(L_X/L_{\text{BOL}}\) ratios are found only when X-ray luminosities are statistically well measured and corrected by the interstellar absorption, not by the total absorption. It should also be emphasized that 30 Dor is an extreme environment, more akin to starbursts than a good representative of the Large Magellanic Cloud (LMC) population.

In the LMC, N11 is the second largest H\textsc{ii} region, just after the giant H\textsc{ii} region 30 Dor. The less extreme properties of N11 make it much more representative of LMC H\textsc{ii} regions and clusters of massive stars. Besides, the lower concentration of stars implies less source confusion, and hence should lead to more reliable results.

Star formation has been very active in N11, with no less than four recognized OB associations: LH9, LH10, LH13, and LH14 (Lucek & Hodge 1970). The stellar feedback has restructured the surrounding interstellar material. Notably, the winds and supernova explosions of the massive stars in LH9 have gradually carved a cavity, giving rise to an expanding superbubble some 120 pc in size (Rosado et al. 1996). This expansion probably triggered the formation of LH10 at the periphery of the superbubble (Walborn & Parker 1992). In turn, the massive stars of LH10 are now beginning to blow bubbles (Nazé et al. 2001), triggering further new star formation in their surroundings (Barbá et al. 2003).

N11 is clearly one of the best sites to study the interplay between stars and the interstellar medium. This interaction, often violent, produces X-ray emission. Using a 30 ks ROSAT Position Sensitive Proportional Counter observation, Mac Low et al. (1998) reported the first detection of X-rays in N11. This ROSAT observation revealed the presence of extended areas of diffuse emission, where the brightest sources are associated with the N11L supernova remnant (SNR) and within the superbubble around LH9. Further investigation was performed with a 30 ks XMM-Newton observation, which provided the first detection of point sources in the field (Nazé et al. 2004). While stars in LH9...
remained unresolved, this XMM observation unveiled in LH10 a mixture of diffuse emission and point sources associated with some of the most massive stars of the cluster. A detailed X-ray analysis of N11 requires a combination of both high sensitivity and high spatial resolution, which became possible with our new, deep X-ray investigation of N11 using the Chandra X-Ray Observatory. This observation will lead to several analyses, and this first paper discusses the point-source population. Our aim is to uncover the nature of the point sources and to find whether or not the properties of the stars in N11 differ from similar objects in the Galaxy. This paper is organized as follows. Section 2 presents the data and their reduction. Section 3 introduces the catalog of X-ray sources and their global properties. Section 4 discusses extended and possible with our new, deep X-ray investigation of N11 using both high sensitivity and high spatial resolution, which became some of the most massive stars of the cluster.

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2. OBSERVATIONS AND DATA REDUCTION

The Chandra ACIS-I observations of N11 were made in six separate segments within two months in 2007. As summarized in Table 1, the exposure time of each segment was 42–49 ks and the roll angle ranged from 130° to 188°. The pipeline products of the observations were reduced and analyzed using our own IDL-based analysis tools (e.g., Wang 2004) as well as the official software for the Chandra Interactive Analysis of Observations (CIAO; version beta1-4.0) together with the calibration database (caldb 3.4.0) and other publicly available routines (e.g., XSPEC version 12.7.0). It should be noted that our detection procedure was shown to provide results comparable to those of ACISExtract (Johnson et al. 2013), and this was checked on this data set by a quick run of that tool.

We used the light curve cleaning routine “lc_clean” to remove time intervals of significant background flares when count rates deviated by more than 3σ or a factor of ≥1.2 from the mean rate of individual observations. This cleaning, together with a correction for the dead time of the six observations, resulted in a total of 280 ks useful exposure for the subsequent analysis.

A combination of source detection algorithms (wavelet, sliding-box, and maximum likelihood centroid fitting) were applied to unsmoothed data in three bands: soft (S) 0.5–2 keV, hard (H) 2–8 keV, and total (T) 0.5–8 keV (Wang 2004). Briefly, the wavelet detection was first used to find the initial source candidates with a high threshold of local false detection probability \( P < 10^{-5} \). Then, background maps were constructed by removing the wavelet-detected sources and by conducting a median averaging or smoothing of the three input images on scales much greater than the point-spread function (PSF) to achieve an intensity uncertainty \( \sim 10\% \). These background maps, insensitive to the exact details of the construction procedure, were again used to search for sources, this time using a sliding-box algorithm (the so-called map detection mode). Finally, a maximum likelihood centroiding algorithm was used, still using the count background map, to derive the best centroid positions for the sources (Wang 2004).

This process was applied independently to each energy band. Our final source list contains sources with local false detection probability \( P < 10^{-6} \) in at least one band (Poisson statistics were used in calculating the significance of a source detection above the local count background). The sensitivity of the source detection depends on the size of the PSF as well as the local background level and effective exposure, which all vary with position, especially with the off-axis angle of the detected sources. The source detection, though optimized for point-like sources, includes a few strong peaks of diffuse X-ray emission, chiefly associated with the SNR N11L, about 7' west of the field center (for more on this object, see W. Sun et al., in preparation). Some of these sources associated with peaks of the diffuse emission are only detected in the S band.

Once source positions were identified, the source count rates needed to be estimated. With this in mind, it must be remembered that the most precise effective exposure times are evaluated in narrow energy bands. Therefore, we calculated the net (background-subtracted) count rates in four sub-bands (\( S1 = 0.5–1 \text{ keV} \), \( S2 = 1–2 \text{ keV} \), \( H1 = 2–4 \text{ keV} \), \( H2 = 4–8 \text{ keV} \)), and they were later added to form the rates in the broader bands (\( S \), \( H \), and \( T \)). We thus first constructed effective exposure maps in these four sub-bands.\(^6\) The construction of these exposure maps assumed a power-law spectrum of photon index 1.7 and accounted for the telescope vignetting and bad pixels as well as the quantum efficiency variation of the instrument, including the time-dependent sensitivity degradation, which is particularly important at low energies (\( < 1.5 \text{ keV} \)). Figure 1 shows such a merged effective exposure map, illustrating the features of the bad pixel removal, CCD gaps, observation dithering, etc., as well as the overall field coverage. In order to treat uniformly both strong and weak sources, source counts for each subband were

\(^{6}\) These exposure maps, combined to apply to the \( S, H \), and \( T \) bands, were also used in the source detection procedure in a standard way.
then extracted within the 70% energy-encircled radius (EER) of the PSF, whose size depends on the off-axis angle of the source in the exposure and of the energy band under consideration. A background correction using the background map constructed earlier was applied. Finally, count rates were derived by dividing source net counts by their effective exposure times (values at the source positions in the exposure map of the energy band under consideration), leading to equivalent on-axis values. It should be noted that the presented count rates have thus been corrected for the full PSF and for the effective exposure, which accounts not only for the telescope vignetting, but also for the degradation of the detector sensitivity over time. Therefore, the actual number of counts in a detection aperture is not simply a count rate multiplied by an exposure of 280 ks. The difference could be up to a factor of ~2, depending on a source’s spectral shape.

We extract an ACIS spectrum for each source detected with signal-to-noise ratio (S/N) > 10. The on-source spectral extraction circle has the same radius as was used for the source removal, while the local background spectrum is estimated from a concentric annulus with an inner radius equal to two times the circle radius and an outer radius twice as large. Detected sources are removed from the background region. The background spectrum is normalized by accounting for bad pixels and boundaries of the CCDs as well as source removal. We obtain the averaged response matrices of each source spectrum, using the weights derived from on-source 0.5–2 keV band counts in the detector coordinates of individual observations. The spectrum is further adaptively binned to achieve a background-subtracted signal-to-noise ratio greater than 2.5 in each bin.

We compared the positions of a few well-identified X-ray sources with their (known) optical counterparts. With this in mind, we considered only OB stars, since they are rather bright sources of X-rays, whereas no other stellar X-ray emitter was known a priori in the field (though several other sources may have possible stellar counterparts, see below, but these were not known a priori). We found no significant systematic offset (<0.5′), and therefore no astrometry correction was applied to the X-ray data. However, we caution that these sources lie at large off-axis angles, so the uncertainties in their X-ray positions may be large, but the absence of bright X-ray sources with well-established optical counterparts prohibits us from fine-tuning the astrometry to 0.1′ accuracy.

3. POINT-SOURCE CATALOG

Using the detection procedure described in the previous section, we found 165 sources in N11: 43 of them were detected with the highest confidence or smallest $P$ value in the $S$ band, 5 in the $H$ band, and 117 in the $T$ band. Among these, 74 were detected in all three bands, 56 only in two bands, and 35 only in one band (22 for $S$, 2 for $H$, and 11 for $T$—while the total band often maximizes the signal-to-noise ratio, some very soft or very hard sources are more easily detected in only the soft or hard band, for example, nearby stars and diffuse emission peaks in the soft band, and faraway accreting sources and active galactic nuclei (AGNs) in the hard band). Table 2 lists for each detected source its position, count rate in the total band and hardness ratios $HR_1 = (H - S)/(H + S)$ and $HR_2 = (S - T)/S$, as well as its off-axis angle, number of counts, estimated background counts, and effective exposure (ks) in the detection aperture. (11) The labels “$T$,” “$S$,” or “$H$” mark the band in which a source is detected with the most accurate position that is adopted in Column 2.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

| Source | CXOU Name | $\delta$ (\degree) | Count Rate (counts ks$^{-1}$) | $\theta$ | Counts | Bkgd Counts | Exp (ks) | Flag |
|--------|-----------|------------------|-------------------------|------|--------|-------------|---------|------|
| 1      | J045427.48–662518.0 | 1.8 | 1.05 ± 0.10 | −0.17 ± 0.13 | 8.4 | 183 | 42.6 | 191 | $T$ |
| 2      | J04534.92–662402.1 | 1.5 | 1.16 ± 0.10 | 0.02 ± 0.10 | 7.6 | 210 | 33.6 | 217 | $T$ |
| 3      | J04538.74–662207.1 | 2.4 | 0.21 ± 0.06 | ... | 8.5 | 77 | 44.8 | 223 | $T$ |
| 4      | J04540.30–662404.8 | 1.5 | 1.72 ± 0.13 | −0.39 ± 0.09 | 7.5 | 251 | 35.7 | 178 | $T$ |
| 5      | J04544.20–662377.4 | 1.7 | 1.00 ± 0.09 | 0.25 ± 0.10 | 8.0 | 193 | 40.3 | 218 | $T$ |
| 6      | J04543.47–662318.9 | 1.3 | 0.66 ± 0.08 | 0.08 ± 0.14 | 6.9 | 121 | 24.1 | 208 | $T$ |
| 7      | J04544.36–662551.0 | 1.2 | 1.83 ± 0.15 | −0.99 ± 0.15 | 6.7 | 213 | 27.7 | 144 | $S$ |
| 8      | J04544.89–662597.1 | 1.0 | 0.41 ± 0.07 | 0.34 ± 0.17 | ... | 7.3 | 96 | 32.3 | 221 | $T$ |
| 9      | J04546.22–663146.7 | 1.9 | 0.77 ± 0.12 | ... | 0.26 ± 0.19 | 8.2 | 95 | 31.5 | 117 | $T$ |
| 10     | J04546.51–662543.0 | 1.2 | 1.29 ± 0.13 | −1.00 ± 0.15 | −0.43 ± 0.08 | 6.5 | 205 | 60.8 | 158 | $S$ |

Notes. The energy bands were defined as follows: 0.5–1.0 ($S_1$), 1.0–2.0 ($S_2$), 2.0–4.0 ($H_1$), and 4.0–8.0 keV ($H_2$); soft band $S = S_1 + S_2$, hard band $H = H_1 + H_2$, and total band $T = S + H$. Columns: (1) Running source number. (2) Chandra X-Ray Observatory source name, following the Chandra naming convention and the IAU Recommendation for Nomenclature (e.g., http://cdsweb.u-strasbg.fr/iau-spec.html). (3) Position uncertainty (1σ) calculated from the maximum likelihood centroiding and an approximate off-axis angle ($r\sigma$) dependent systematic error $0.2 + 1.4r/8S^2$ (an approximation to Figure 4 of Feigelson et al. 2002), which are added in quadrature. Note that they may be overestimated; see Getman et al. (2005, in particular Figure 9). (4) On-axis source total count rate—the sum of the exposure-corrected count rates in the four narrow bands. (5) and (6) The hardness ratios defined as $HR_1 = (H - S)/S$ and $HR_2 = (S - T)/S$, listed only for values with uncertainties less than 0.2. (7) Off-axis angle ($\theta$, in units of arcminutes). (8)–(10) Raw counts, background counts, and effective exposure (ks) in the detection aperture. (11) The labels “$T$,” “$S$,” or “$H$” mark the band in which a source is detected with the most accurate position that is adopted in Column 2.
ACIS-I intensity image of N11 in the 0.5–2 keV band and detected sources (Table 2). The circles mark the regions of individual sources (radius = 1σ uncertainty in position, see text for details), the dashed line marks the boundaries of the merged ACIS FOV (Figure 1), and the positions of the main clusters are indicated by ellipses.

The gas-column density of $N_H \sim 1 \times 10^{21}$ H-atom cm$^{-2}$ (assuming solar abundances). This conversion should be a good approximation (within a factor of two) for $N_H \lesssim 3 \times 10^{21}$ H-atom cm$^{-2}$. The corresponding conversion to a source-frame luminosity in the same band is $\sim 2.4 \times 10^{36}$ erg s$^{-1}$ (counts s$^{-1}$)$^{-1}$ at the LMC distance of 50 kpc.

The ACIS-I total band (unsmoothed) image is shown in Figure 2 with the detected X-ray sources marked, while Figure 3 shows a smoothed three-color map of the X-ray emission in N11 as well as an H$\alpha$ image for comparison. The smoothed images show that many point sources are superposed on diffuse emission. As the source detection is based on Poisson statistics and the image smoothing uses Gaussian statistics, there appear to be additional point-like sources (to eyes) in the smoothed images. These are artifacts of the smoothing procedure. We will not consider these false sources caused by noise bumps.

We also conducted tests for timing variability. We first carried out Kolmogorov–Smirnov tests as well as $\chi^2$ tests on the total-band light curves of the 41 sources with detected S/N > 4, which are well covered by the six observations. For $\chi^2$ tests, light curves were adaptively binned so that each bin contains at least 20 counts. The sources J045509.20−663018.5 and J045702.07−662257.1 (#32 and 158, Figure 4) show significant variabilities in the total band at confidence levels of 5σ and 3σ, respectively. They possess no counterpart within 1′′ (see Section 3.1) and their nature remains unknown. Variability examination in the S and H bands yields no additional results. The separate analysis of individual observations for all 117 sources that are not near the CCD gaps (with a 12′′ margin to account for the dithering effect) in any of the observations yields only one positive result: J045539.69−662959.5 (#64) shows an apparent variation in the S band during observation #8210 at a confidence level of $\sim 3\sigma$ (Figure 4). This source is a known quasar candidate (see Section 3). However, with so many sources studied in two independent bands (the third one being related to the other two since $S + H = T$), this latter variability detection is not inconsistent with the occurrence of such an event by pure chance, and hence is marginal.

Figure 5 shows the hardness ratios of the 53 sources with both ratios known with errors less than 0.2: most (48) of the sources have HR$_1 \sim 0$ and HR$_2 \sim 0.75$, indicating relatively hard sources. To assess the contamination of the catalog by background AGNs, we have characterized the X-ray source number–flux relation (NFR) in N11. This NFR analysis uses only the 141 sources detected in the total band, for

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**Figure 2.** ACIS-I intensity image of N11 in the 0.5–2 keV band and detected sources (Table 2). The circles mark the regions of individual sources (radius = 1σ uncertainty in position, see text for details), the dashed line marks the boundaries of the merged ACIS FOV (Figure 1), and the positions of the main clusters are indicated by ellipses.

**Figure 3.** Left: tri-color montage of X-ray intensities: (red) 0.5–2 keV, (green) 2–4 keV, and (blue) 4–8 keV. The images are adaptively smoothed with the CIAO routine CSMOOTH. The smoothing scales are calculated separately in the soft and hard bands and with the signal-to-noise ratio $\sim 3$; the subtracted background is estimated locally in CSMOOTH. Right: H$\alpha$ image for comparison. The main regions are labeled.

(A color version of this figure is available in the online journal.)
homogeneity and to avoid biases toward soft or hard sources. Eddington bias\(^7\) was corrected following the approach of Wang (2004). We may compare the derived NFR to the log(N)–log(S) presented by Moretti et al. (2003, and references therein). However, the X-ray absorption through N11 (from NRAO survey,\(^8\) \(N_H \sim 4.3 \times 10^{20} \text{ H-atom cm}^{-2}\)) is substantially higher than that toward the Chandra deep fields (foreground absorption \(1.6 \times 10^{20} \text{ cm}^{-2}\)). Correcting for this difference, we find an expected number of AGNs in a field of 91 (Figure 6), i.e., most of our sources are in fact extragalactic background objects. Indeed, a few AGNs have been identified in the field: a correlation of our source list with quasar tables in Vizier results in the identification of sources #11 (Kim et al. 2012; Kozłowski & Kochanek 2009) and #38, 45, 64, 98, 117, and 123 (Kozłowski & Kochanek 2009). Note, however, that some parts of the nebula are filled with molecular clouds, and these locally enhanced absorption columns may reduce the number of detectable AGNs.

3.1. Optical and Infrared Counterparts

We searched for counterparts to our X-ray sources in several catalogs: the USNO-B1.0 Catalog (Monet et al. 2003), the Guide Star Catalog V2.3.2 (GSC, Lasker et al. 2008), the 2MASS All-Sky Catalog of Point Sources (Cutri et al. 2003), the Magellanic Clouds Photometric Survey (MCPS; Zaritsky et al. 2004), the IRSF Magellanic Clouds Point Source Catalog (Kato et al. 2007), the DENIS Catalogue toward Magellanic Clouds (DCMC; Cioni et al. 2000), and \(JHK_s\) photometry of N11 young stellar objects ([HKN2006]; Hatano et al. 2006).

To find the optimal correlation radius, we first searched for the closest counterpart to each X-ray source and derived the number

\(^7\) The so-called X-ray Eddington bias implies that intrinsically faint sources statistically appear to have higher fluxes than the other way around.

\(^8\) http://asc.harvard.edu/toolkit/colden.jsp
of matches as a function of radius: at large radii, the number of matches is proportional to the squared radius, as expected by chance coincidences. A best correlation radius of 1″ was found and used to derive the final list of counterparts (Table 3): 71 of the 165 sources have at least one counterpart within 1″. Among these, 13 objects are known massive stars (see Table 6 and Section 4), 2 are OB candidates (#130 and 136; Hatano et al. 2006), and 1 is a HAeBe candidate (#63; Hatano et al. 2006). Two additional sources have been misidentified with stars in the past: Src #98, proposed to be an HAeBe candidate on the basis of the photometry (Hatano et al. 2006), is in fact a quasar (Kozłowski & Kochanek 2009), while Src #24, identified as a young stellar object (Whitney et al. 2008), actually corresponds to the nucleus of a background galaxy (Gruendl & Chu 2009).

The photometric measurements of the counterparts appear to be coherent in different catalogs. We therefore focus on IRSF, because it contains the largest number of counterparts (58 sources) among the tested catalogs. Considering the sources with full $JHK_s$ photometry available, color–magnitude and color–color diagrams can be constructed (Figure 7). Besides massive stars, counterparts appear to the right of the main sequence, suggesting that they are young stars that are still forming; however, known quasars also have similar photometric properties, requiring additional investigation.

To this end, we further used Hα, [O iii], and [S ii] images taken with the MOSAIC camera on the Blanco 4 m Telescope at the Cerro Tololo Inter-American Observatory. The Hα observations consisted of three dithered exposures of 300 s each for each location; the bulk of N11 was imaged on 2008 December 5 and the periphery of N11 was imaged on 2010 January 9. The [O iii] $\lambda$5007 observations and the [S ii] $\lambda\lambda$6716, 6731 observations consist of four dithered 450 s exposures for each location; these images were obtained on 2011 October 31. We have also used infrared observations made with the Spitzer Space Telescope. The Spitzer images and photometry of point sources of N11 are taken from the previous work by Gruendl & Chu (2009),
Figure 8. [S\textsc{ii}] images (10′′ on a side) centered on X-ray point sources whose positions are shown by 1σ radius circular regions. The saturated stellar images appear as white spots in these figures.

(A color version of this figure is available in the online journal.)

who made a photometric catalog and identified young stellar objects for the entire LMC. These images have been used to inspect the counterparts to the X-ray point sources. Among the three optical images, the [S\textsc{ii}] image is the most useful because the diffuse emission from ionized gas is not as strong and confusing as that in H\alpha and [O\textsc{iii}]. Among the infrared images, we have primarily used the 3.6 and 8.0 μm images.

Figure 8 shows 10′′ × 10′′ cutout [S\textsc{ii}] images overplotted with error circles (radius from Column 3 of Table 2) centered on the derived positions of all 165 X-ray sources. These images are useful for an independent confirmation or rejection of optical counterparts. Although some of the error circles have radii ≪1′′, the combined errors in the X-ray and optical astrometry may reach ∼1′′. We have conservatively used a minimum correlation radius of 1′′ for identification of optical counterparts; however, only three sources (43, 78, and 107) have optical counterparts that are within 1′′ but outside the error radius. The results of our investigation are noted in Table 4, including the Spitzer counterparts of the X-ray point sources.

To assess the physical nature of the optical and infrared counterparts of the X-ray sources, we have assembled spectral energy distributions (SEDs) for the sources that have photometric measurements available. The following passbands and catalogs have been used: $UBVI$ from MCPS, $JHK_s$ from Two Micron All Sky Survey (2MASS) and IRSF, and IRAC bands from Gruendl & Chu (2009). These SEDs are presented in Figure 9.

The SEDs of known massive stars, such as sources #48, 77, 97, 110, 115, 126, 141, 142, 146, and 157, have a distinct shape that falls off toward long wavelengths, following the Rayleigh–Jeans law. While the SEDs of stars can be diagnosed by their downturn in infrared, the nature of the stars need to be estimated from their photometric colors and magnitudes. For each object with a stellar SED, we use the MCPS $UBVI$ and IRSF $JHK$ photometry to determine colors in several combinations of bands (such as $U − B$, $B − V$, $V − I$, $J − K$, etc.), compare the observed colors with those of dwarfs (luminosity class V) and supergiants (luminosity class I) to assess its spectral type, and compare the observed magnitude with the expected absolute magnitude to determine its distance.

We find that Sources #130 and 136 are B2 giants, in agreement with the suggestion of candidate OB stars by Hatano et al. (2006); sources #108, 139, and 145 are late-type B dwarfs; and source #106 may be a type A0 star. The distances that we derived for these objects are $\geq 50$ kpc, and are thus in the LMC.
Table 4

Counterparts to X-Ray Sources Found within 1″ of Our Dedicated Data (Optical [S ii] Image and 3.6 and 8.0 μm Spitzer Data) and Suggested Nature of the Sources

| Src in [S ii]? | Spitzer | Comment | Suggested Nature |
|---------------|---------|---------|------------------|
|               | (3.6 μm²?) | (8.0 μm²?) | (d) | Name | |
| 1             | y       | y       | 0.56 | 045440.29−662407.9 | Point source + Diffuse X-ray Galaxy at z = 0.024 |
| 4             | y       | y       | 0.24 | 045442.38−662227.6 | SED rises in IR Galactic K0V Star at 4.5 kpc |
| 7             | y       | y       | 0.39 | 045446.61−662004.1 | SED peaking at 3μm AGN (see Section 3.) |
| 11            | y       | y       | 0.27 | 045447.28−662759.2 | SED rises in mid-IR AGN (AGN) |
| 13            | y       | y       | 0.50 | 045448.37−662102.9 | N11L SNR |
| 14            | y       | y       | 0.50 | 045448.37−662102.9 | N11L SNR |

Notes. Detections in only two Spitzer channels are noted, but a few named sources have detections only in the other channels. Some sources are quoted with a visual detection (“y” in the third and/or fourth columns) without a name listed for the Spitzer counterpart: this happens because the automated detection misses some sources, especially faint ones in high-background regions.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Using the same conversion factors as for known massive stars (see Section 4.2), the X-ray luminosities of these sources in the total band amount to $\sim 5 \times 10^{32} \text{ erg s}^{-1}$ for the three late-B stars and the A0 star, and $1\to2 \times 10^{33} \text{ erg s}^{-1}$ for the two B2III stars. This leads to a log($L_X/L_{\text{BOL}}$) of $-2.6$ for the A0 star, $-3.2$ for the late-B stars, and $-4.6$ for the B2III stars. Such luminosities are too high for even flares of PMS companions or flares of these stars themselves (Robrade & Schmitt 2011),
Table 5
Number of Counterparts from Table 4 Per Category

| Nature                        | Number |
|-------------------------------|--------|
| Galactic objects              | 11     |
| Massive stars (or Star groups) in LMC | 13     |
| AB stars in LMC               | 6      |
| AGNs or galaxies              | 9      |
| (AGN)                         | 19     |

but too low in comparison with those of known HMXBs in the LMC (>10^{34} erg s^{-1}; Shtykovskiy & Gilfanov 2005). Furthermore, such high log(L_X/L_BOL) ratios are not compatible with embedded wind shocks (such stars would not have the strong mass-loss necessary for this mechanism, anyway). In the absence of further information, it seems likely that objects other than these AB stars are the true X-ray emitters: chance alignment with a foreground (soft) source or a background (hard) source or localized peak in soft diffuse emission. In this context, it should be noted that #106, 108, and 130 seem to emit mostly soft X-rays, while the emissions of #136 and 139 appear much harder.

The cooler stars are all in the Galactic foreground: source #56 is a known K0 star; sources #5 and 28 are G stars; 25, 43, 78, 87, and 109 are K stars; 54, 95, and 107 are M stars. In two cases, sources #25 and 109, the colors at long wavelengths suggest a K spectral type, but the star appears too bright in UB. It is likely that they are Sirius-like systems in which the K star dominates the emission in longer wavelengths and the white dwarf dominates the emission in shorter wavelengths. The individual results of the stellar counterpart analysis are given in Table 4 and a summary by category is provided in Table 5.

AGNs and galaxies can also be diagnosed from SEDs by their distinct shape which rises toward long wavelengths in the infrared (Donley et al. 2008; Dey et al. 2008). For example, sources #11, 24, 36, 38, 45, 63, 64, 98, 117, and 123 have well-populated SEDs rising in the IR and are thus good candidates for AGNs. Indeed, seven of them (#11, 38, 45, 64, 98, 117, and 123) have been identified as quasars by Kozłowski & Kochanek (2009) and one (#24) is a resolved galaxy with a prominent nucleus (Gruendl & Chu 2009). Since stellar emission is not expected to be flat and since many of these objects are detected only in the IR (not in optical), we suggest that objects with flat SEDs may also be AGNs. In Table 4, we use “AGN” to denote confirmed objects and “(AGN)” for candidates.

Finally, our observation did not reveal active HMXBs among the known massive stars in N11 (see Section 4), and the late B stars newly identified using photometry (see previous paragraphs) display no definitive sign of being in HMXBs. We have further examined the data to see whether other bright X-ray sources would have (unknown) OB counterparts, following the method of Shtykovskiy & Gilfanov (2005) and using the information available on the nature of the sources, when such information exists. As in 30 Dor (Townsley et al. 2006a) and some other LMC clusters (Oskinova 2005), no HMXB was detected in N11, although its cluster LH9 is old enough (7.0 ± 1.0 Myr; Mokiem et al. 2007) for its initially most massive stars to have undergone supernovae. Adopting the classical Salpeter initial mass function (IMF) for the observed stellar content and with upper cut-off at 150 M_☉, up to 10 stars initially more massive than 60 M_☉ might have been present in the cluster. However, the production efficiency of HMXBs is low, which could explain the absence of detections in N11 (e.g., Oskinova 2005; Clark et al. 2008, though not necessarily in...
agreement with the Galactic census of HMXBs from Helfand & Moran (2001).

4. MASSIVE STARS

4.1. The Massive Star Population in the Chandra Field

Of the four massive star clusters in N11, two (LH9 and 10) are covered by our Chandra observation. Their stellar content is quite well known. The first complete study (Parker et al. 1992, hereafter PGMW) provided spectroscopic classification for about 75 stars, 43 of which are O-type objects. Using Hubble Space Telescope (HST) data to disentangle the two compact OB groups HD 32228 in LH9 and PGMW 3204/9 in LH10, Walborn et al. (1999) provided spectral classification for 20 additional hot stars, while the Very Large Telescope Flames Survey led to the discovery of 25 additional O-type stars, including a potential runaway star of type O2.5III (Evans et al. 2006, hereafter ELST). In total, 1 Wolf–Rayet, 81 O-type stars, and 80 B-type stars are now known in the Chandra field of view (FOV). Spectral monitoring of ELST further indicated a binary fraction of 36% among the massive stars of LH9-10, which is quite low for such stars (Sana & Evans 2011). Finally, Mokiem et al. (2007) performed atmosphere modeling on 22 of the ELST targets, leading to the first accurate determination of their physical properties.

Note that four O and nine B of ELST stars are outside the Chandra FOV.
These studies showed that LH9 and LH10 appear to be very different from each other. Indeed, LH9 is the most extended and the richest cluster in N11. It is dominated by a compact group of stars collectively referred to as HD 32228, which contains one Wolf–Rayet star of the carbon sequence (Brey 9) and many late O-type stars (Walborn et al. 1999). Furthermore, stars in LH9 have blown a large superbubble (Rosado et al. 1996). In contrast, the LH10 cluster, still partly embedded in its natal cloud, appears to be rather young, with wind-blown bubbles of limited size (Nazé et al. 2001) and the earliest O-type stars still present (Evans et al. 2006). The IMF in these clusters was constrained to $\Gamma_{LH10} = -1.1 \pm 0.1$ and $\Gamma_{LH9} = -1.6 \pm 0.1$ (PGMW), confirming that there are many more high-mass stars in LH10 than in LH9. These facts, together with the higher reddening of LH10, indicate the relative youth of LH10 compared to LH9 (about 2 Myr difference, see PGMW and Mokiem et al. 2007). Because of the age difference and of the position of LH10 at the periphery of the LH9 superbubble, it was suggested that the pair constitutes an example of sequential star formation (Walborn & Parker 1992).

4.2. Detection of Massive X-Ray Emitters in N11

The poorer PSFs of the previous X-ray observations of N11 (ROSAT: Mac Low et al. 1998; Dunne et al. 2001; XMM-Newton: Nazé et al. 2004) did not lead to unambiguous detections of X-ray emission associated with the OB stars of LH9 or LH10. At first sight (see Figure 2), the Chandra X-ray point sources do not appear to be obviously clustered toward LH9, LH10,
or their periphery due to the large number of background sources (Section 3). However, correlating the list of X-ray sources (see Table 2) with the list of OB stars with known spectroscopic classification led to 13 positive matches. As a last check, we further inspected the X-ray image by eye and one additional X-ray source associated with an O-type star was clearly spotted (see, e.g., the many contours showing a source associated with PGMW 3100 in Figure 12). An extraction run specific to OB stars (see below) yields a 2σ detection for this object and a false detection probability just below that of the detected objects (i.e., much higher than for the truly undetected O stars). It lies near a rather bright point source and on the edge of diffuse emission, which probably explains its non-detection by the automated detection algorithms.

Table 6 lists the properties of these 14 OB stars with detected X-ray emission. The first five columns report the X-ray source number, the ELST or PGMW identification, the spectral type, and binary status (from ELST: Walborn et al. 1999, or PGMW). In addition, for each object we derived the color excesses $E(B - V)$ from the $BV$ photometry using the intrinsic colors from Martins & Plez (2006). Galactic reddening toward the LMC was estimated to be 0–0.15 mag by Oestreicher et al. (1995); as the reddening of some of our stars is ~0, we will consider the Galactic contribution negligible and we therefore calculate the absorbing columns $N_H$ using a gas-to-dust ratio of $N_H/E(B-V) = 2.4 \times 10^{22}$ H-atom cm$^{-2}$ mag$^{-1}$, typical of the LMC (Fitzpatrick 1986). The bolometric luminosities, when not estimated by Mokiem et al. (2007), were also derived from $BV$ photometry with intrinsic colors and bolometric corrections from Martins & Plez (2006); they were derived using the properties of the earliest component if the object is a binary with the types of the two components known (“SB2” in Table 6). These derived absorbing columns and bolometric luminosities are presented in the sixth and seventh columns of Table 6. The last two columns of that table give the unabsorbed flux (in the 0.5–10 keV band) and log($L_X/L_{BOL}$) ratio (see also Figure 10). These X-ray luminosities were derived by different methods depending on the source brightness. Five of the sources have enough counts (>80 counts) for a rough spectral analysis (Figure 14). They were modeled within XSPEC using an absorbed thermal model (XSPEC models mekal and vphabs, both with metal abundances set to 0.3 times solar). The results of these fits are shown in Table 7. As is usual for massive stars (e.g., Nazé et al. 2012b), two solutions of rather similar quality can be found, one with high $T$ and low $N^\text{add}$, and the other with low $T$ and high $N^\text{add}$. It is difficult to choose between the two solutions since the exact amount of additional absorption $N^\text{add}$ due to the cool wind beyond the interstellar absorption cannot be fixed a priori: the formal best-fit one is listed in Table 7.
Spectral Properties of the Brightest OB Stars

| Source | $N_{\text{H}}^\text{ abs}$ | $kT$ | Norm | $\chi^2$ (dof) | $F_X$ | $F_X^{\text{obs}}$ |
|--------|-----------------|-------|-------|--------------|-------|-----------------|
| 134    | 0.20 ± 0.00     | 1.41 ± 0.01 | 2.28 ± 0.01 | 1.06 (10) | 1.99 | 1.99 |
| 142    | 0.24 ± 0.00     | 0.67 ± 0.00 | 15.4 ± 0.00 | 1.14 (18) | 5.39 | 6.32 |
| 146    | 0.95 ± 0.00     | 0.81 ± 0.00 | 7.54 ± 0.00 | 1.88 (6)  | 1.93 | 2.84 |
| 152    | 0.05 ± 0.00     | 0.19 ± 0.00 | 8.04 ± 0.00 | 0.63 (10) | 3.40 | 6.31 |
| 164    | 0.25 ± 0.00     | 1.35 ± 0.00 | 4.63 ± 0.00 | 1.84 (2)  | 2.16 | 4.27 |

Notes. Fitted models have the form $\text{vphabs}(N_{\text{H}}^\text{ISM}) \times \text{vphabs}(N_{\text{H}}^\text{ abs}) \times \text{apec}$ with the interstellar absorption $N_{\text{H}}^\text{ISM}$ listed in Table 6 and the abundances of all components set to 0.3 times solar. The lower and upper limits of the 90% confidence interval are shown as subscripts and superscripts, respectively; fluxes are given in the 0.5–10 keV band and unabsorbed fluxes are corrected by the interstellar absorption only; spectra were grouped to achieve a minimum of 10 counts per bin.

This is not surprising since B-type stars are generally not bright X-ray emitters and the X-ray emission apparently associated with such objects has generally been attributed to a flaring PMS companion (see, e.g., Sana et al. 2006; Evans et al. 2011) or to an accreting compact companion. Generally, the B stars with detected X-ray emission have early types (B0–B0.5) and their emission is due to embedded wind shocks as in O-type stars. This could apply to Src #110 (ELST 33), an early-type B star whose count rate is correspondingly low with a signal-to-noise ratio of ~2 and whose $L_X/L_{\text{bol}}$ is similar to that of O stars in our sample.

Most of the detected sources correspond to hot, O-type objects. Two of the sources correspond to the compact OB groups HD 32228 and PGMW 3204/9, while another source

However, it must be stressed that this dual solution ambiguity only affects the derivation of intrinsic emission levels, but has no impact on the derivation of $L_X/L_{\text{bol}}$ ratios, as the X-ray luminosities used in this context are corrected by the interstellar absorption only. For the fainter sources, we derived fluxes by converting the count rates. Using the on-axis response matrices and a thermal model with a temperature $kT = 0.6$ keV absorbed by the $N_H$ determined above (both with metal abundances set to 0.3 times solar), we derived conversion factors between count rates (in counts ks$^{-1}$) and unabsorbed fluxes (in erg cm$^{-2}$ s$^{-1}$) of 0.5–2 $\times$ 10$^{-14}$. Using a temperature of 0.3 keV would increase the fluxes by less than a factor of two.

One only of the detected sources is a B-type star, and thus the detection fraction for these objects is low, ~1.3% (1 out of 80).
is associated with the compact H II region N11A and its small cluster (see individual discussion for these below). Excluding the 19 stars in these compact groups, the fraction of detected O-type stars is 16% (10 out of 62). When ranked by magnitude or spectral types, it appears that the hottest and/or earliest objects are preferentially detected, as could be expected (the detection fraction is 57% for O2–5 stars, 25% for O5.5–O7 stars, and 3% for O7.5–9.7 stars). However, when one looks into detail, things are not so simple. For example, of the four O2–3 stars present in the field, only two are detected: the one belonging to the PGMW 3204/9 compound (which thus contains additional massive stars emitting X-rays) and ELST 31. The latter object is neither a known binary nor the brightest earliest-type star (ELST 26 being slightly brighter than ELST 31).

To gain further insight into the global properties of the OB star population, we estimated the total-band count rates of all OB sources in the field using their cataloged positions and corresponding 90% EER (i.e., not 70% EER as before) to minimize the potential effect of the astrometry errors in the X-ray data and the objects’ positions. Results for the 13 detected O stars are of course consistent with the count rates reported in Table 2. On the other hand, for the 52 undetected O stars, these measurements allowed us to derive upper limits, which we adopted to be the 3σ errors on the count rates. These upper limits on the count rates were transformed into upper limits on the unabsorbed flux as was done above for the fainter detected sources.

Table 8 summarizes the properties of these 52 undetected O-type stars present in the Chandra FOV. Columns 1 and 2 give the star numbers in ELST and PGMW, respectively, the third and fourth columns indicate the spectral type and binary status, the fifth column provides the bolometric luminosity as derived from the photometric color excess \(BV\) given by Mokiem et al. (2007) when available or as derived status, the fifth column provides the bolometric luminosity as derived from massive stars emitting X-rays and ELST 31. The latter object is neither a known binary nor the brightest earliest-type star (ELST 26 being slightly brighter than ELST 31).

Since the X-ray emission depends on the winds, it may be expected that massive stars with different wind properties, such as low metallicity, will show a different level of X-ray emission. In addition, deviations from that “canonical” \(L_X - L_{BOL}\) relation are also found in exceptional cases. For example, while most massive O+OB binaries are not much harder or brighter (small overluminosities of 0.2 dex at most; Oskinova 2005; Sana et al. 2006; Nazé 2009; Nazé et al. 2011, 2013) than single stars, a few systems appear to be hard and overluminous because an X-ray-bright wind–wind collision is present (e.g., HD 93403: Rauw et al. 2002; Cyg OB2#9: Nazé et al. 2012a). Magnetically confined winds may also lead to overluminosities in strongly magnetic stars (e.g., \(\theta^1\) Ori C; Schulz et al. 2000; Gagné et al. 2005).

In N11, results from spectral fits suggest rather large \(\log(L_X/L_{BOL})\) ratios and high plasma temperatures. Indeed, except for the HD 32228 compound, all detected sources clearly lie above the Galactic \(\log(L_X/L_{BOL}) = −7\) relation (Figure 10) and temperatures of 0.7–1.3 keV are recorded here, when temperatures of 0.2 or 0.6 keV (depending of the trade-off between temperature and absorption mentioned above) are usually observed for Galactic O stars. While it is possible that the stellar census is limited by confusion (with several neighboring stars mistaken as one, leading to errors in the bolometric luminosity estimates), it is also very probable that we detect only the X-ray-bright tip of the massive star population. The detected objects would then be wind–wind interacting systems or strongly magnetic objects; they would therefore not be fully representative of the properties of the O-type population in N11. In this context, it may be worth noting that, excluding the stars in compact groups, only 20% (2 out of 10) of the X-ray sources are known binaries, i.e., a smaller fraction than in the N11 population (36%, ELST)—although the limited monitoring of ELST may have missed the multiplicity of some objects. Further study should be undertaken to clarify the status of the detected objects (bona fide single stars, colliding-wind binaries, magnetic objects). To obtain a more representative idea of the actual X-ray emission level from massive stars in the LMC, we may turn to the undetected O stars: their stacked emission suggests a lower \(\log(L_X/L_{BOL})\) value of \(-7.3\). This is a value comparable to Galactic values (e.g., Carina nebula; Nazé et al. 2011), which contradicts a priori intuitions (lower metallicity → weaker winds → fainter X-ray emission). Future observations are, however, needed to confirm the overall representativeness of this \(\log(L_X/L_{BOL})\) value for massive stars and to enlarge the study of the \(L_X/L_{BOL}\) ratio in the LMC.

4.2.1. Sources in LH9: HD 32228 and Its Environment

The main component of LH9, the compact group also known as HD 32228, is clearly detected in our observations (Figure 11). Its X-ray emission follows the visible one, i.e., it is not a simple point source and looks rather extended. The morphology is actually reminiscent of a point-like source superimposed on a small region of diffuse emission, itself immersed in the fainter superbubble emission from the whole cluster. We have extracted spectra of each of these three regions (see Tables 7 and 10).

The emission peaks at the position of the stellar group encompassing the Wolf–Rayet Brey 9 or BAT99-10. Since this evolved object belongs to the carbon sequence, it is not expected to emit significant amounts of X-rays if single (Oskinova et al. 2003). The total luminosity from all O-type stars in the HD 32228 compound amounts to \(\sim 7.5 \times 10^{39}\) erg s\(^{-1}\), implying...
a log($L_X/L_{\text{BOL}}$) ratio of $-7.1 \pm 0.1$, which is fully compatible with the Galactic value (Table 6).

The surrounding area ("near HD 32228," see Table 10), once cleaned of the superbubble "background" contribution, presents a harder spectrum than the emission associated with the superbubble itself. Its high temperature and high absorption suggest the emission to be dominated by the overall X-rays from unresolved stellar objects, most probably O and PMS stars. In contrast, another region in LH9 with higher surface brightness ("inside LH9," see Table 10) displays a spectrum very similar to the superbubble itself—only a few deviant high-energy bins, maybe spurious, are detected as a very high temperature plasma with low emission measure. To the limits of our data, the X-ray emission associated with the superbubble around LH9 thus appears rather uniform if one excludes HD 32228 and its surroundings.

### Table 8
Properties of the Undetected O-type Stars Known in the Field

| ELST | PGMW | Sp. Type | Bin.? | log($L_{\text{BOL}}/L_{\odot}$) | $N_H$ ($10^{22}$ cm$^{-2}$) | $L_X^{\text{abs}}$ ($10^{33}$ erg s$^{-1}$) | log($L_X/L_{\text{BOL}}$) |
|------|------|----------|-------|----------------|------------------|-----------------|----------------|
| 007  | 08 Ib (f) | N | 5.72 | 0.58 | <2.02 | <−7.00 |
| 010  | 1310 O9.5 III + B1-2: | SB2 | 5.42 | 0.29 | <3.92 | <−6.41 |
| 011  | OC9.5 II | SB1 | 5.49 | 0.43 | <0.66 | <−7.25 |
| 013  | 3223 O8 V | SB2 | 5.66 | 0.48 | <2.43 | <−6.86 |
| 018  | 3053 O6 III(f) | N | 5.64 | 0.43 | <1.42 | <−7.07 |
| 019  | O8-9 III-V(f(f)) | SB2 | 5.40 | 0.24 | <1.68 | <−6.76 |
| 020  | O5 I(nfp) | Y | 5.50 | 0.14 | <4.32 | <−6.45 |
| 022  | O6.5 II(f) | N | 5.45 | 0.29 | <0.98 | <−7.04 |
| 026  | O2.5 III(?) | N | 5.92$^a$ | 0.26 | <6.64 | <−6.68 |
| 029  | OC9.7 Ib | N | 5.21$^a$ | 0.34 | <0.42 | <−7.17 |
| 032  | 3168 O7 III(f) | N | 5.43$^a$ | 0.38 | <1.69 | <−6.79 |
| 041  | O6.5 Iaf | Y | 5.17 | 0.19 | <2.53 | <−6.35 |
| 043  | 1519 O7 III + B0: | SB2 | 5.12 | 0.14 | <1.69 | <−6.48 |
| 045  | O9-9.5 III | N | 5.15$^a$ | 0.26 | <1.97 | <−6.44 |
| 046  | O9.5 V | Y | 4.91 | 0.05 | <3.94 | <−5.90 |
| 049  | 1110 O7.5 V | SB1 | 5.04 | 0.07 | <0.70 | <−6.78 |
| 052  | O9.5 V | SB2 | 4.95 | 0.19 | <9.15 | <−5.57 |
| 058  | O5.5 V((f)) | N | 5.72$^b$ | 0.12 | <2.11 | <−6.53 |
| 059  | 1125 O9 V | SB1 | 4.84 | 0.05 | <0.99 | <−6.43 |
| 060  | 3058 O3 V((f*)) | N | 5.57$^a$ | 0.53 | <1.27 | <−7.05 |
| 061  | O9 V | N | 5.20$^a$ | 0.50 | <4.08 | <−6.17 |
| 063  | O9: Vn | SB2 | 4.88 | 0.22 | <8.87 | <−5.52 |
| 071  | O8: V | SB2 | 4.84 | 0.19 | <4.22 | <−5.80 |
| 080  | 3173 O7: V + O9: | N | 4.91 | 0.29 | <1.27 | <−6.39 |
| 087  | O9.5 Vn | N | 4.91$^a$ | 0.38 | <0.99 | <−6.50 |
| 091  | O9 V | Y | 4.78 | 0.41 | <2.82 | <−5.91 |
| 108  | O9.5 V | N | 4.56 | 0.19 | <2.39 | <−5.76 |
| 122  | O9.5 V | N | 4.37 | 0.00 | <0.84 | <−6.03 |
| 123  | O9.5 V | N | 4.58$^a$ | 0.02 | <1.41 | <−6.01 |
| 1194 | O9.5:IV | 4.92 | 0.29 | <0.84 | <−6.58 |
| 1200 | O6:Vp | C? | 5.65 | 0.89 | <1.13 | <−7.18 |
| 1239 | O7:O8:V: | 4.90 | 0.24 | <1.27 | <−6.38 |
| 1288 | O9 V | 4.45 | 0.12 | <1.13 | <−5.98 |
| 1292 | O9:III: | 4.67 | 0.77 | <1.13 | <−6.20 |
| 1363 | O8.5 Iaf | 5.63 | 0.41 | <1.55 | <−7.02 |
| 1365 | O9 V | 4.47 | 0.05 | <1.27 | <−5.95 |
| 1377 | O8 V | 4.73 | 0.12 | <1.41 | <−6.16 |
| 1388 | O9.7 Iab | 5.70 | 0.36 | <1.69 | <−7.06 |
| 1396 | O7 Vp | 5.24 | 0.14 | <1.55 | <−6.63 |
| 1431 | O9 V | 4.58 | 0.14 | <1.27 | <−6.06 |
| 1481 | O7 V((f)) | 5.22 | 0.17 | <1.83 | <−6.54 |
| 1483 | O6.5 III(f) | 5.59 | 0.24 | <1.83 | <−6.91 |
| 1486 | O6.5 V | 5.07 | 0.14 | <1.55 | <−6.46 |
| 3016 | O9.5:V | 4.68 | 0.34 | <1.13 | <−6.21 |
| 3045 | O9.5 III | 4.55 | 0.36 | <1.13 | <−6.08 |
| 3073 | O6.5 V | 5.00 | 0.41 | <1.83 | <−6.32 |
| 3089 | O8 V | 4.91 | 0.36 | <1.13 | <−6.44 |
| 3102 | O7 V | 5.44 | 0.41 | <1.33 | <−6.76 |
| 3103 | O9.5:IV: | 4.29 | 0.29 | <1.41 | <−5.72 |
| 3115 | O9 V | 4.67 | 0.41 | <1.97 | <−5.96 |
| 3123 | O8.5 V | 4.92 | 0.38 | <1.41 | <−6.35 |
| 3126 | O6.5 V | 5.28 | 0.65 | <1.27 | <−6.76 |

*Note.* $^a$ The bolometric luminosity comes from the fits of Mokiem et al. (2007).
4.2.2. Sources in LH10

Figure 12 shows a close-up of the LH10 cluster. In this region, six point-like sources are detected. They correspond to five O-type stars (ELST 31, 38, and 50, and PGMW 3070 and 3120) and one compact group (PGMW 3204/9). The brightest source, PGMW 3070, actually appears as a tight cluster in the HST images. The point-like source associated with the two subclusters display a slightly elongated shape, probably indicating that they are not truly point-like sources. Their flux is also too high for a single star, with \( \log(L_X/L_{\text{BOL}}) \) of \(-6.0\) for the sole PGMW 3070. The fluxes of the other sources in LH10 are also higher than observed in Galactic single O-type stars. This is especially the case for the bright binary ELST 50, which presents the highest \( \log(L_X/L_{\text{BOL}}) \) ratio: even taking into account the presence of two stars, the X-ray source is still about five times brighter than expected. The ratio appears closer to the Galactic value only for PGMW 3204/9, considering the sum of the individual luminosities of this stellar group’s components—the detailed stellar content is well known in this area, but maybe nowhere else in LH10. It is also interesting to note that in our data, PGMW 3204/9 appears as bright as PGMW 3070, whereas it was half as bright during the XMM observations (compare our Figure 12 with Figure 11 of Nazé et al. 2004): this may indicate some variability in its high-energy emission, which is not expected for single, “normal” massive stars and is therefore generally associated with an orbital or rotational modulation. Further monitoring of these objects is needed to ascertain their nature.

Some diffuse emission is also present throughout the field, especially to the southwest of the cluster near PGMW 3070 and 3120. In this region, a wind-blown bubble was detected by Nazé et al. (2001). However, the same authors found another expanding bubble east of PGMW 3204/9 and ELST 50 with similar expansion velocity, but it does not appear to be associated with diffuse emission as bright as the former. Higher velocity structures were also detected by Nazé et al. (2001), but appear to the south and west of the X-ray bright region, not coincident with it. It could be noted that the diffuse emission, which appears to be centrally peaked rather than bright-rimmed, corresponds to the region of highest stellar density—the eastern part of LH10 is much less crowded. This could suggest that at least part of the X-ray emission actually comes from unresolved stars, as in the case of NGC 602 in the SMC (Oskinova et al. 2013). This hypothesis seems confirmed when the spectrum of that diffuse emission is analyzed (Table 10): two thermal components are present, one with a low temperature typical of soft diffuse emission and one with higher temperature, most probably stellar in origin (both components have similar luminosities in the 0.3–2.0 keV band).

4.2.3. Sources in N11A

The compact H II region N11A, lying to the east of LH10, probably harbors the youngest optically visible stars in the field (Heydari-Malayeri et al. 2001). This region is associated with the “star” PGMW 3264 or ELST 28, which is actually the earliest component of a compact stellar group composed of seven objects. The associated X-ray emission is rather strong and a comparison of its shape with that of its neighbors suggests some extension. Since the earliest object was proposed to be a highly obscured mid O-type star (Heydari-Malayeri et al. 2001; Evans et al. 2006), strong X-ray emission from that star is not expected. The X-ray emission may instead be associated with wind–wind interactions between the cluster members or a combination of several unresolved sources. Unfortunately, the spectrum of this source is difficult to extract since it lies on the edge of some data sets. The crude X-ray spectrum only points to a high temperature, but the high noise prevents us from drawing definitive conclusions. These results should therefore be taken with caution (especially since a low absorbing column is also favored by the noisy data, clearly at odds with the heavy extinction expected within a dense cloud). N11A deserves...
further investigation, especially to assess its stellar content in detail.

4.3. Diffuse Emissions in N11

As can be seen in the color image of the Chandra FOV (Figure 3), soft diffuse emission pervades the N11 region. On the basis of the surface brightness, we defined 11 regions to be further analyzed and 3 regions displaying lower emission were chosen as backgrounds (see Figure 13 and Table 9 for their positions).

For the study of these regions, we need to estimate the non-X-ray background contribution which is not vignetted by the telescope. This estimate uses the ACIS stowed background database, which has been processed with charge transfer inefficiency and gain corrections.10 The background level in each chip of individual observations was further normalized according to the ratio of its count rate to that of the stowed data in the 10–12 keV band, where events are almost completely due to the non-X-ray background.

Spectra of the chosen regions were extracted, with the non-X-ray background being subtracted from each one. Regions of twice the 70% EER around each point source were removed. Note that for visual presentation of the smoothed diffuse X-ray intensity maps, we replace the source-removed region with values interpolated from data in the surrounding bins (see, e.g., Figure 13). The spectra have been analyzed in the 0.3–2 keV range, beyond which there is little signal (Figure 14).

To take into account the variations of the sensitivity across the FOV, the spectral fitting was done in two steps. First, each background (or combination of background) was individually fitted, although the background spectral shape remains rather similar, with the most varying parameter being the overall intensity level. Second, the sources were fitted by models of the form $\text{vphabs} \sum \text{apec}$ + model$_B$, where the former component represents the true spectrum of the diffuse source (metal abundances of the absorption and thermal emission models were accordingly fixed to 0.3) and the latter represents the best-fit background model determined before (these were fixed to the best-fit background model with the normalization factors scaled by the effective surface ratio—keyword BACSCAL—of the source and background regions). The results of these fits are presented in Table 10. The spectral analysis of two additional regions of LH9 that display a higher surface brightness is also presented in this table.

The results from spectral fitting allow us to compare the selected regions. First, we examine temperature variations. The spectra of all regions display a thermal component at low temperatures ($kT \sim 0.2$ keV). For LH9 and LH10, an additional, hotter plasma component ($\gtrsim 1$ keV) was needed to obtain a good fit, suggesting that it is associated with unresolved stellar objects (PMS, O stars). This contamination is not negligible since it represents about one-third of the total flux associated with the diffuse sources. Its stellar origin is supported by the analysis of the region (called “middle”) situated between LH9–LH10 and the northern limit of the FOV. The spectrum of the latter region does not require the presence of a high temperature component; indeed, only a few stars are scattered across this region and the stellar contribution is thus expected to be negligible here. Note that a fit of the LH9 spectrum where the abundance of the low-temperature component is allowed to vary does not improve the $\chi^2$.

Regarding absorptions, a value of $N_H = 7 \times 10^{21}$ H-atom cm$^{-2}$ is generally found for the LT fits and a lower value

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10 Following the procedure described in http://cxc.harvard.edu/contrib/maxim/acisbg/.
Figure 13. Definition of the extraction regions for diffuse emission (see Table 10 for their analysis).

(A color version of this figure is available in the online journal.)

Table 9

| Name            | R.A.           | Decl.         | Semi-axes         | Pos. Angle | Counts | Net Count Rate |
|-----------------|----------------|---------------|-------------------|------------|--------|----------------|
|                 | (hh:mm:ss)     | (°:′:″)       | (′′ × ′′)         | (°)        |        | (10^−3 count s^−1) |
| North           | 04:55:53.2     | −66:16:39.4   | 84.1 × 69.4       | 0          | 1165   | 1.5 ± 0.3      |
| Middle          | 04:56:19.9     | −66:21:46.2   | 233.2 × 138.7     | 0          | 17570  | 18.1 ± 0.6     |
| Middle-w        | 04:55:54.6     | −66:22:21.8   | 106.6 × 66.1      | 58.9       | 4158   | 5.1 ± 0.3      |
| Middle-se       | 04:56:45.7     | −66:22:07.9   | 124.0 × 66.4      | 0          | 4799   | 6.1 ± 0.3      |
| Middle-ne       | 04:56:22.6     | −66:20:32.4   | Circle (63.7)     |            | 2314   | 2.4 ± 0.2      |
| LH10            | 04:56:44.8     | −66:24:56.2   | 36.1 × 28.2       | 322.9      | 752    | 1.44 ± 0.12    |
| East of LH9     | 04:57:07.8     | −66:26:52.2   | 53.1 × 73.8       | 323.7      | 2066   | 2.2 ± 0.2      |
| West of LH9     | 04:56:02.8     | −66:30:28.9   | 118.1 × 67.9      | 0          | 5970   | 8.8 ± 0.3      |
| LH9a            | 04:56:35.6     | −66:28:34.8   | 178.8 × 106.2     | 21.3       | 13985  | 21.2 ± 0.5     |
| Inside LH9      | 04:56:56.3     | −66:28:53.6   | Circle (29.5)     |            | 739    | 0.61 ± 0.12    |
| Near HD 32228a  | 04:56:34.7     | −66:28:27.2   | Annulus (5.15)    |            | 321    | 0.58 ± 0.08    |
| Bkgd 1          | 04:55:29.9     | −66:18:19.7   | Circle (66.2)     |            | 1612   | 1.51 ± 0.16    |
| Bkgd 2          | 04:55:23.3     | −66:29:38.6   | Circle (60.7)     |            | 1556   | 2.16 ± 0.16    |
| Bkgd 3          | 04:55:48.8     | −66:25:11.6   | Circle (54.1)     |            | 1087   | 2.19 ± 0.17    |
| Annulus A       | 04:56:56.3     | −66:28:53.6   | Annulus (30.55)   |            | 1400   | 2.89 ± 0.14    |
| Annulus B       | 04:56:34.7     | −66:28:27.2   | Annulus (30.60)   |            | 2363   | 5.80 ± 0.18    |

Notes. Counts: number of counts in spectra in the 0.3–2.0 keV energy band (without background correction). Net count rate: count rate in the 0.3–2.0 keV energy band for the source region, after correction for the background contributions (non-X-ray and local ones) or count rate in the 0.3–2.0 keV energy band for the background region, after correction for the non-X-ray background contribution.

a The spectrum of the X-ray point source associated with HD 32228, extracted in the 5″ region surrounding the star, was presented in Table 7 while the region “near HD 32228” corresponds to an annulus of inner radius 5″ and outer radius 15″, and the spectrum for “LH9” excludes a region of 15″ around HD 32228, i.e., those are three distinct regions.

is found for the 2T fits. The larger absorption value might in fact be an artifact; if we use only one component to fit the spectra of LH9 or LH10, the best fit also yields a higher absorption for these objects—this may also be linked to the temperature-absorption trade-off mentioned before. Unfortunately, the spectra of the other diffuse sources are too noisy to make a meaningful 2T fit. With this caveat in mind, one can, however, see the remarkable homogeneity of the derived spectral parameters with the exception of harder components being needed when stellar clusters are located (LH9, LH10).

5. SUMMARY

This paper reports the first results of a very deep Chandra observation of the giant H ii region N11 in the LMC. Soft diffusion emission is seen throughout the field, but its spectra
reveal some point-source contamination. Thanks to the long exposure (∼300 ks) and the high spatial resolution, 165 X-ray point sources were detected in the field with 3 showing significant temporal variability. Our *Chandra* observation thus increases by more than a factor of five the number of point sources known in N11. Keeping in mind that the sensitivity varies across the field, it must be noted that the faintest detected sources have count rates of about 0.04 counts ks$^{-1}$, which correspond to luminosities of about $10^{32}$ erg s$^{-1}$ in the 0.5–8.0 keV energy band. Diffuse emission is also detected throughout the field, but the harder X-ray emission from some regions indicates contamination from unresolved stars.
Most of the X-ray sources are background objects seen through the LMC, but there are also 11 Galactic stars. However, 14 OB stars are clearly detected in X-rays, 3 of them corresponding to compact clusters (HD 32228, PGMW 3204/9, and N11A). The known binaries are not preferentially detected in N11, although this conclusion might be biased by our incomplete knowledge of the stellar multiplicity. Indeed, these stars could correspond to interacting winds systems or magnetic objects, as may be suggested by their rather high luminosities and plasma temperatures. In this context, it should be noted that changes are detected in massive stars of LH10 compared to older XMM data. Follow-up observations are therefore needed to ascertain the nature of these sources. The stacked emission of the undetected O stars yields a log($L_X/L_{bol}$) of $-7.3 \pm 0.3$. This suggests that the intrinsic X-ray emission of massive stars could be similar in the Galaxy and the low-metallicity environment of N11. This is unexpected, as X-ray emission from massive stars is known to arise in their line-driven stellar winds whose properties are known to vary with metallicity. Further observations are, however, needed to confirm this result.

These Chandra data will be used for several follow-up studies, notably on the SNR N11L (W. Sun et al., in preparation), the diffuse emission, and a global multiwavelength study of N11.

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