MASSIVE STARS IN THE Cl 1813-178 CLUSTER: AN EPISODE OF MASSIVE STAR FORMATION IN THE W33 COMPLEX

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ABSTRACT

Young massive ($M > 10^4 M_\odot$) stellar clusters are a good laboratory to study the evolution of massive stars. Only a dozen of such clusters are known in the Galaxy. Here, we report about a new young massive stellar cluster in the Milky Way. Near-infrared medium-resolution spectroscopy with UIST on the UKIRT telescope and NIRSPEC on the Keck telescope, and X-ray observations with the Chandra and XMM satellites, of the Cl 1813-178 cluster confirm a large number of massive stars. We detected 1 red supergiant, 2 Wolf-Rayet stars, 1 candidate luminous blue variable, 2 Of, and 19 OB stars. Among the latter, twelve are likely supergiants, four giants, and the faintest three dwarf stars. We detected post-main-sequence stars with masses between 25 and 100 $M_\odot$. A population with age of 4–4.5 Myr and a mass of $\sim 10,000 M_\odot$ can reproduce such a mixture of massive evolved stars. This massive stellar cluster is the first detection of a cluster in the W33 complex. Six supernova remnants and several other candidate clusters are found in the direction of the same complex.

Key words: infrared: stars – stars: evolution

Online-only material: color figures

1. INTRODUCTION

An understanding of the mechanisms of formation, evolution, and end state of massive stars is fundamental for the studies of galaxies at all redshifts. Massive stars contribute to the chemical enrichment of the interstellar medium with their strong winds and by exploding as supernovae. Massive stars are the most luminous stars, can easily be detected in external galaxies, and provide distance estimates. They are the sources of the most energetic phenomena in the universe, gamma-ray bursts (e.g., Woosley & Bloom 2006).

The availability of large surveys of the Galactic plane at radio and infrared wavelengths opens a golden epoch for studying the formation, evolution, and environments of massive stars. More than 1500 new candidate stellar clusters have been discovered, and among them several young clusters rich in massive stars may be hidden (Messineo et al. 2009).

In Messineo et al. (2008, hereafter referred to as Paper I), we presented the serendipitous discovery of a young massive cluster, Cl 1813-178, in the Galactic disk at $l = 12^\circ$, with a spectroscopically identified population of massive stars, a red supergiant (RSG) star, two blue supergiants (BSGs), and one Wolf-Rayet (WR) star. Here, we present a follow-up study of the cluster. Near-infrared photometry and spectroscopy, and X-ray observations, reveal a large number of massive stars.

The cluster is located in the W33 complex and is associated with two supernova remnants (SNRs), SNR G12.72−0.00 and G12.82−0.02, and the highly magnetized pulsar associated with the TeV $\gamma$-ray source HESS J1813−178. Interestingly, the W33 complex appears to contain several other candidate stellar clusters and several SNRs. Clusters do form in large complexes (e.g., Beuther et al. 2007), and their spatial distribution varies from cloud to cloud, indicating that several external and internal triggers can be at work (e.g., Clark et al. 2009). W33 is an ideal laboratory to investigate various issues about massive stars and multi-seeded star formation, and to verify the presence of triggered sequential star formation, which is suggested by the presence of SNRs. The association of the stellar cluster with two SNRs can shed light on the initial masses of the supernova progenitors and on the fate of massive stars.

We describe the observations and data reduction in Section 2, and analyze the spectra and the cluster color–magnitude diagram (CMD) in Section 3. A discussion on the massive members and spectrophotometric distances is presented in Sections 4 and 5. Cluster age and mass are derived in Sections 6 and 7. An overview of candidate clusters in the direction of the W33 complex is given in Section 8. Finally, our findings are summarized in Section 9.

2. OBSERVATIONS AND DATA REDUCTION

2.1. IR Photometry

Photometric measurements from the near-infrared Two Micron All Sky Survey (2MASS) catalog (Skrutskie et al. 2006),
the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) catalog (Benjamin et al. 2003) as well as from the Naval Observatory Merged Astrometric Data set (NOMAD; Zacharias et al. 2004) were used.

Images of the central cluster region with the J, H, and \( K_s \) filters were obtained during two nights of observation, 2008 June 23–24, using the near-IR camera SofI mounted on the ESO NTT (Moorwood et al. 1998). We used SofI in large-field mode with a pixel size of 0′′.288 and a total field of view of 4′9 × 4′9 (Figure 1). For each filter, we performed a random dithering pattern of 14 images and reached a total exposure time of 840 s, 1176 s, and 1680 s in \( J, H, \) and \( K_s \), respectively. Each image is a combination of 50, 70, and 100 exposures, each one 1.2 s long, in \( J, H, \) and \( K_s \) bands, respectively.

Data reduction was performed using standard IRAF routines. For each filter, we obtained a sky image by median-combining the dithered frames and subtracted the sky image from each frame. Flat fielding was performed by using the SpecialDomeFlat template, which applies the appropriate illumination correction, as described in the SofI User Manual. Finally, the dithered frames were averaged into a single image. Standard crowded-field photometry, including point-spread function modeling, was carried out on each image using DAOPHOT II/ALLSTAR (Stetson 1987). The internal photometric accuracy was estimated from the rms frame-to-frame scatter of multiple star measurements (0.03 mag < \( \sigma_J \sim \sigma_H \sim \sigma_{K_s} < 0.06 \) mag for \( 8 < J \sim H \sim K_s < 18 \)). The instrumental magnitudes were converted into the 2MASS photometric system. The 2MASS catalog was used as an astrometric reference frame. For stars that were saturated on the SofI images, magnitudes were taken from the 2MASS catalog.

2.2 Near-IR Spectroscopy

Spectroscopic observations of the brightest stars were carried out with NIRSPEC at the Keck Observatory under program H243NS (PI: Kudritzki) on 2008 July 24. The \( K \)-filter and a 42″ × 0′.570 slit were used, covering from 2.02 to 2.45 \( \mu \)m with a resolution of \( R = 1700 \). For each target, two nodded exposures of 10 s each were taken. We observed a total of 23 stars with NIRSPEC (see Tables 1 and 7).

Additional spectroscopic data were taken with the UKIRT 1–5 \( \mu \)m Imager Spectrometer (UIST) at the UKIRT Observatory. We used the short-\( K \) grism in combination with a 120″ × 0′.12 slit, covering from 2.00 to 2.26 \( \mu \)m at a resolution \( R = 1800 \). We also used the long-\( K \) grism to cover the spectral range from 2.204 to 2.513 \( \mu \)m at a resolution \( R = 1900 \). Typically, each target was observed with the long-\( K \) grism. When CO bands were not detected, a second spectrum was taken with the short-\( K \) grism. Integration times varied from 30 to 60 s per exposure, and the number of exposures varied from 8 to 20 s. The 39 stars observed with UKIRT, including a few chance detections, are listed in Tables 1 and 7.

Pairs of frames with nodded positions were subtracted and flat fielded. The stellar traces were straightened using a two-dimensional de-warping procedure. We wavelength calibrated the spectra with arc lines. We corrected the spectra for atmospheric absorption and instrumental response by dividing the observed spectra by the spectrum of a reference star. Reference stars were of B type (from B2 to B9). The Br \( \gamma \) and H\( \epsilon \) lines of the telluric spectrum were eliminated with linear interpolation. The signal to noise of the spectra varied from 40 to 150.

2.3 X-ray Data

The cluster is located in the vicinity of the HESS J1813–178 pulsar wind nebula (Helfand et al. 2007). Several X-ray observations of this region have been performed in order to identify the pulsar associated with the HESS source. Helfand et al. (2007) presented a catalog of 75 point sources detected with the Chandra satellite. We cross-correlated the Chandra catalog with the 2MASS point-source catalog and identified a total of 44 matches (Paper I). Using the XMM satellite, Funk et al. (2007) detected seven X-ray sources in the surrounding area of HESS J1813–178.

3. ANALYSIS

3.1 Spectral Classification

Spectral classification was performed by comparing the spectra with spectral atlases (e.g., Hanson et al. 1996, 2005; Figer et al. 1997; Martins et al. 2007; Kleinmann & Hall 1986; Wallace & Hinkle 1996).

11 Based on data taken within the observing program 081.D-0371.
12 An overall uncertainty of ±0.05 mag in the zero-point calibration in all the three bands has been estimated.
13 The astrometric procedure provided rms residuals of ≈0′′.2 in both the right ascension and declination.
14 Data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation.
15 The United Kingdom Infrared Telescope (UKIRT) is operated by the Joint Astronomy Centre on behalf of the Particle Physics and Astronomy Research Council.
We observed a total of 60 stars and detected 24 early-type stars and 36 late-type stars. In addition, we considered the previous observations reported in Paper I, which added an extra early-type star (no. 11) to our new sample. The observed stars were divided into candidate cluster members and non-members and are listed in Tables 1 and 7. We first listed the sample of stars given into candidate cluster members and non-members and are listed star (no. 11) to our new sample. The observed stars were divided observations reported in Paper I, which added an extra early-type supergiants (see the Appendix B).

### 3.1.2. Wolf-Rayet Stars

Star 4 is a known WR star of type WN7 (number 8 in Hadfield et al. 2007). Star 7 has similar emission lines at 2.114 μm, 2.166 μm, and 2.189 μm. By comparing it with the spectral atlas of Figer et al. (1997), star 7 appears to be another WN7 star (see Figure 4).

### 3.1.3. Candidate Luminous Blue Variables

The spectrum of star 15 is dominated by He I lines at 2.058 μm and 2.112 μm, and Br γ line in emission. Faint Mg II lines are detected at 2.138 μm and 2.144 μm. The type of detected lines and the line profiles indicate that star 15 is a P-Cygni B supergiant. Its spectrum is similar to that of the cLBV star in the W51 region (Clark et al. 2009). More information on the stellar photometric variability is needed to firmly confirm that it is another LBV star.

### 3.1.4. O-type Stars

Spectra of O and B stars have hydrogen lines, helium lines, and other atomic lines (e.g., C iv, N iii, C ii, and Mg ii). Hydrogen and helium lines are usually seen in absorption; they may be in emission in supergiants. The Br γ line is the only hydrogen line detectable in K band. The He I transitions at 2.058 μm and 2.112 μm are usually detected in late-O and early-B stars. The He II line at 2.189 μm appears only in O-type stars. With our resolution, the He II line at 2.189 μm may be present down to O9.5I or O9V.

The spectrum of star 6 has a strong He I line at 2.058 μm in absorption, C iv lines at 2.069 μm and 2.079 μm in emission, and...
strong emission line at 2.11 μm (probably due to He i/N iii/C iii), and an He i absorption line at 2.189 μm. N iii at 2.25 μm is seen in emission. There is an indication for a faint C iv line at 2.083 μm and a N iii line at 2.10 μm. The simultaneous presence of He i, He ii, and C iv lines is typical of an O-type star. The strengths of the He i and He ii absorption lines, as well as the detection of N iii at 2.25 μm, indicate a O6–O7f+.

The spectrum of star 16 has Br γ line in emission, an He i line at 2.058 μm with P-Cygni profile, and an He i/N iii line at 2.112 μm. An He ii line at 2.189 μm is seen in absorption. A faint line is seen in emission at 2.105 μm. Only an indication for a C iv line at 2.08 μm is visible. The spectrum resembles that of an O8–O9II star, similar to HD151804 (Morris et al. 1996).

Stars 18, 19, and 20 have He i lines at 2.058 and 2.112 μm in absorption, a N iii line at 2.115 μm in emission, and Br γ line in absorption. An He ii line at 2.189 μm clearly appears in absorption. The absence of C iv lines, and the presence of N iii and He ii lines, suggest a late O-type (O7–O9).

The spectra of stars 2, 3, 11, 12, 13, 14, 17, 21, 22, 23, 24, 25, and 26 have He i lines at 2.058 μm and Br γ line in absorption. From the relative strengths of the Br γ and He i lines (Hanson et al. 1996), the presence of He i in emission at 2.058 μm, and the lack of He ii lines, these stars appear to be B0–B3 supergiants.

3.1.5. B-type Stars

Here, we list all detected early-type stars, which do not have He ii lines. These may be B-stars or O9 dwarfs. With our resolution, the He ii line at 2.189 μm may be present down to O9.5I or O9V. Once the He ii line disappears, assigning a spectral type and luminosity class can turn into a quite degenerate issue. This degeneracy may be partly broken if the absorption components of the Br γ line and of the He i lines are sufficiently filled in by the stellar wind contribution. Typically, an He i line at 2.112 μm in absorption is observed down to B8Ia stars, while the same line is not detected in dwarfs/giants later than B3V. Such matters are highly dependent on the quality of the spectra.

From a comparison with the atlas of Hanson et al. (1996), stars 2, 3, 11, 12, 13, 14, 17, 21, 22, 23, 24, 25, and 26 appear to be likely stars with types from B0 to B2.

The spectra of stars 2 and 13 have an He i line at 2.058 μm in emission, an He i line at 2.112 μm, and Br γ line in absorption. From the relative strengths of the Br γ and He i lines (Hanson et al. 1996), the presence of He i in emission at 2.058 μm, and the lack of He ii lines, these stars appear to be B0–B3 supergiants.
Figure 4. Spectra of star 4, which is an already known WR star (Hadfield et al. 2007), and star 7, which is a newly detected WR star. For comparison, a spectrum of a WN7 star, WR120, is presented from the atlas of Figer et al. (1997). The rest wavelengths of He\textsubscript{ii}, He\textsubscript{i}, H\textsubscript{i}, and C\textsubscript{iii}/N\textsubscript{iii} lines are also marked.

The spectra of stars 3, 22, 24, 25, and 26 have an He\textsubscript{i} line at 2.112 μm in absorption as well as Br\textsubscript{γ} line in absorption. Star 17 has Br\textsubscript{γ} line in absorption and a trace of He\textsubscript{i} at 2.112 μm. These are likely B0–B3 stars or O9–B3 stars (depending on the luminosity class).

The spectra of stars 11, 21, and 23 have Br\textsubscript{γ} line in absorption and He\textsubscript{i} lines at 2.058 and 2.112 μm in absorption. These spectra are typical of early B-type stars.

Star 12 has Br\textsubscript{γ} line in absorption. The lack of He\textsubscript{i} at 2.112 μm in absorption suggests that star 12 has a spectral type later than a B8I or B3–B4V star.

The spectrum of star 14 has Br\textsubscript{γ} in absorption, an He\textsubscript{i} line at 2.112 μm in absorption, an indication for an He\textsubscript{i} line in emission at 2.058 μm, and a faint He\textsubscript{i} line at 2.113 μm in emission. The lack of He\textsubscript{i} at 2.189 μm and the presence of He\textsubscript{i} lines suggest that star 14 is a BSG star with spectral type between B0 and B3.

The spectrum of star 11 is shown in Paper I. Stars 2 and 3 were also observed with NIRSPEC in 2008 April (Paper I), and we obtained the same spectral classification.

3.2. Photometric Results

3.2.1. Cluster Size

We assume as a cluster center the flux-weighted centroid of a 2MASS K\textsubscript{s}-band-smoothed image (R.A. = 18:13:24.15, decl. = −17:53:29.64). We take as a cluster radius the average distance from the cluster center where the surface brightness becomes equal to the average brightness of the surrounding field (3.5′). The 61 spectroscopically observed stars are located within 6.5′ from the cluster center, but predominantly (50) within the cluster radius. Within 3.5′ from the cluster center, we observed 41 stars out of the 48 stars with K\textsubscript{s} < 9.5 mag, and 30 stars out of the 31 stars with K\textsubscript{s} < 9.0 mag.

A fraction of 48% of stars brighter than K\textsubscript{s} = 9.5 mag, within the cluster radius, have early types and are likely to be members. The high degree of completeness of the spectroscopic observations of the bright sample allows for a precise numbering of stars in various post-main-sequence phases (WR, clLBV, RSG, and OB stars).

3.2.2. Color–Magnitude Diagram and Cluster Reddening

In the top panels of Figure 5, we display a (J − K\textsubscript{s}) versus K\textsubscript{s} diagram of 2MASS data points within the cluster radius of 3.5′ as well as a diagram of a comparison field. The same CMD
with deeper SofI data, covering the central 4.9 × 4.9, is shown in the bottom panel of Figure 5.

Several distinct populations of stars are seen in the CMD. There is a sequence of stars at $J - K_s = 0.5$ mag, which we attribute to field stars in the closer Sagittarius–Carina spiral arm. There is a broad sequence with $J - K_s$ from 3 to 6 mag, which is populated mainly by field giant stars in the background of the cluster. Three candidate RSGs were detected from this sequence. Finally, there is a sequence of bright stars with $J - K_s \approx 1.5$ mag and with $K_s$ from 3 to 14 mag (bottom panel of Figure 5). This sequence is seen only in the cluster field, and this is the brightest extension of the cluster sequence.

To confirm and isolate the cluster sequence, we performed a statistical decontamination. 2MASS data were used in order to have a comparison field. We counted the number of stars in a grid of 0.5 mag in ($J - K_s$) and of 1.0 mag in $K_s$. From each bin of the cluster CMD, we subtracted a number of stars equal to that of the corresponding field bin. First, we subtracted all contaminating giant stars (spectroscopically detected), then we continued with a random subtraction. The decontaminated diagram is displayed in the right panel of Figure 5, and different symbols indicate known spectral types. The cluster sequence appears populated by massive stars. An average interstellar extinction of $A_{K_s} = 0.83 \pm 0.2$ mag ($A_V = 9.1$ mag) was estimated by matching the colors of the observed cluster sequence with a theoretical isochrone of solar composition from the Geneva group (Lejeune & Schaerer 2001) and by assuming a power-law extinction curve $A_J \propto \lambda^{-1.9}$ (Messineo et al. 2005). This measurement is independent of age since the isochrones are almost vertical sequences in this plane. An isochrone of 4.5 Myr and solar metallicity, taken from the non-rotating models of the Geneva group, is overplotted on the diagram (Lejeune & Schaerer 2001).

4. LUMINOSITIES OF THE MASSIVE STARS

In the following, we analyze the properties (colors, magnitudes, and luminosities) of massive stars in the Cl 1813-178 cluster, which we list in Table 2. A kinematic distance of 4.8 kpc is used (see section 4.1). For each star, we assumed an intrinsic color consistent with its stellar spectral type (Koornneef 1983; Martins & Plez 2006; Wegner 1994); we used the extinction law by Messineo et al. (2005) and the kinematic distance, and we estimated values of $A_{K_s}$ and $M_K$ (see Table 2). The $M_K$ values were transformed into bolometric magnitudes, $M_{bol}$, by adding the bolometric corrections. The adopted effective temperatures and bolometric corrections per spectral type are given in the Appendix.

4.1. Red Supergiants

Star 1 is the brightest star within the cluster area, $K_s = 3.8$ mag, and is consistent with being a K2–K5 I cluster member (Paper I). From the radial velocity ($V_{LSR}$ = 62 ± 4 km s$^{-1}$) of star 1 (Paper I) and the Galactic rotation curve by Reid et al. (2009), we obtained a revised near kinematic distance of 4.8$^{+0.25}_{-0.28}$ kpc. With intrinsic colors from Koornneef (1983) and bolometric correction, $BC_b$, taken from Levesque et al. (2005), we estimated a luminosity $L_\ast = (9 \pm 7) \times 10^4 L_\odot$.

Stars 32, 38, and 39 have EW(CO) larger than the typical values for red giants. Stars 32 and 38 were observed with NIRSPEC, and their $K$-band spectral coverage allows us to study both the CO band heads and the shape of the continuum. The
large values of EW(CO)s and the absence of water absorption suggest a supergiant luminosity class for stars 32 and 38 (Comerón et al. 2004). Star 39 was observed with UIST on UKIRT, with the K-long filter only, and we do not have information on the shape of its continuum. We derived spectral types M2.5I, M3.5I, and M1I, respectively, by assuming a membership; they are too faint to be RSGs and part of the cluster. For star 4 (O6–O7If+), when using an intrinsic ($H - K$)$_0$ = 0.1 mag and BC$_K$ = −0.01 mag (Martins & Plez 2006), we obtained $M_K$ = −5.87 mag and $L_*$ = (8.2 ± 2.3) × 10$^5$ $L_\odot$. The estimated value of $M_K$ is consistent with the value given for an O6–O7 star by Martins & Plez (2006) and Clark et al. (2005b). Star 16 is another rare O supergiant, an O8–O9If star. By assuming ($H - K$)$_0$ = −0.1 mag and BC$_K$ = −3.84 mag (Martins & Plez 2006), we obtained $M_K$ = −7.32 mag and $L_*$ = (23 ± 6) × 10$^5$ $L_\odot$. Star 16 is the brightest early-type cluster member, and it is located close to the observed Humphreys–Davidson limit for stars with similar effective temperatures (Clark et al. 2005a).

### 4.2. Wolf-Rayet Stars

Star 4, a WN7b, was spectroscopically detected by Hadfield et al. (2007). Hadfield et al. performed a successful color-based selection of candidate WR stars with 2MASS and GLIMPSE data. WRs have an infrared excess (see Figures 5 and 6), which is caused by free–free emission, and do not follow the reddening vector. Star 7 is a newly detected WN7o star, its colors fall within the Hadfield et al. criteria.

For stars 4 and 7, we used intrinsic colors for WN stars with broad and narrow lines, respectively, derived by Crowther et al. (2006a) (see the Appendix B). We obtained an interstellar extinction $A_K$ = 0.7 mag and $A_K$ = 0.8 mag, respectively. By adopting the kinematic distance, BC$_K$ from Crowther et al. (2006a), we obtained $L_*$ = (5.8 ± 2.5) × 10$^5$ $L_\odot$ for star 4 and $L_*$ = (4.8 ± 2.1) × 10$^5$ $L_\odot$ for star 7.

### 4.3. Luminous Blue Variables

Among the observed spectra, we detected one candidate cLBV star (15). LBV stars are rare massive supergiants in transition toward the WR phase (e.g., Conti et al. 1995; Nota et al. 1995; Figer et al. 1997; Conti 1984). Since their evolutionary paths on the CMD are quite uncertain, their detections in stellar clusters are of primary importance. The K-band spectrum of star 15 is similar to that of a P-Cygni–type B supergiant, cLBV, e.g., the [OMN2000]LS1 star presented by Clark et al. (2009). We used CMFGEN, the iterative non-LTE line blanketing method presented by Hillier & Miller (1998), to estimate the physical properties of this supergiant. For details on the modeling, see Najarro (2001), Najarro et al. (2009), and Clark et al. (2009).

The K-band spectra provided the primary diagnostics (the HeI lines at 2.058 $\mu$m and 2.112 $\mu$m, and the MgII lines at 2.138 $\mu$m and 2.144 $\mu$m). We obtained an effective temperature $T_{\text{eff}}$ ≃ 16,000 ± 300 K and a value of $L_*$ = (2.1 ± 1.5) × 10$^5$ $L_\odot$. This value matches the luminosities of the faintest P-Cygni supergiants known in the Milky Way (Clark et al. 2005a, 2009).

### 4.4. OB Stars

We detected 21 OB stars in the Cl 1813-178 cluster. The current data set of medium-resolution K-band spectra allow for a spectral classification of OB stars typically within ±2 spectral types (Hanson et al. 1996). The combination of spectral and photometric properties suggests that we have detected 14 OB supergiants, 4 OB giants, and 3 OB main-sequence stars.

For star 6 (O6–O7If+), when using an intrinsic ($H - K$)$_0$ = −0.1 mag and BC$_K$ = −4.01 mag (Martins & Plez 2006), we obtained $M_K$ = −5.87 mag and $L_*$ = (8.2 ± 2.3) × 10$^5$ $L_\odot$. The estimated value of $M_K$ is consistent with the value given for an O6–O7 star by Martins & Plez (2006) and Clark et al. (2005b).

Figure 6. Upper panel: $K_s$ vs. $J-K_s$ diagram of point sources detected within 3.5′ from the cluster center. The arrow indicates the reddening vector for $A_K = 1.0$ mag, which is calculated by following a near-infrared power law with $a = 1.9$ (Messineo et al. 2005), and by using the extinction ratios $A_{\lambda}/A_K$, $A_{\lambda}/A_K$, $A_{\lambda}/A_K$, $A_{\lambda}/A_K$, $A_{\lambda}/A_K$, $A_{\lambda}/A_K$ of Indebetouw et al. (2005). Symbols are as seen in Figure 5. Bottom panel: GLIMPSE [3.6]−[8.0] vs. [3.6]−[5.8] diagram of point sources detected within 3.5′ from the cluster center. Symbols and arrow are as shown in the top panel.

(A color version of this figure is available in the online journal.)
From a comparison with the $M_K$ values by Martins & Plez (2006) and Panagia (1973), the OB stars 25, 24, and 26 are likely dwarfs, since they have $M_K \lesssim -4$ mag ($L_\ast \lesssim 1.4 \times 10^5 L_\odot$). The OB stars 9, 21, 22, and 23 are probably of luminosity classes III or II, since they are fainter than a typical BSG. Their $M_K$ values range from $-4.7$ to $-5.36$ mag ($L_\ast$ varies from $1.1 \times 10^5$ to $1.5 \times 10^5 L_\odot$). All remaining OB stars are supergiants.

The large spread in magnitudes of OB supergiants ($\sim 3$ mag in $K_s$ band) is not surprising. A similar observational spread is observed in the 2MASS $K_s$ magnitudes of BSGs in Westerlund 1 (Clark et al. 2005b).

### 4.5. X-ray Emitters

X-ray emission may be generated in the circumstellar envelopes of massive stars due to their strong shocked winds (Lucy & White 1980). Single OB stars emit with a typical X-ray luminosity of $L_X = 10^{31}$–$10^{33}$ erg s$^{-1}$ (Pollock 1987) and have a typical ratio between the X-ray and bolometric luminosities of about $10^{-7}$. OB+OB and OB+WN binaries generally have higher luminosities ($L_X = 10^{32}$–$10^{33}$ erg s$^{-1}$; Clark et al. 2008). X-ray emission enables us to characterize the physical condition of stellar atmospheres and to identify binary systems.

X-ray observations of the Cl 1813–178 cluster region were performed by Funk et al. (2007) and Helfand et al. (2007), successfully detecting a large number (75) of X-ray emitters. We looked for possible associations between X-ray emitters and massive members of the Cl 1813–178 cluster (Paper I). All but one X-ray sources with a bright 2MASS counterpart ($K_s < 9.6$ mag) were found associated with early-type cluster members (see Table 3). Two X-ray emitters coincide with WR stars (nos. 4 and 7); six others are associated with OB stars (nos. 2, 3, 5, 6, 8, and 9). The remaining X-ray emitter (star 71; Helfand et al. 2007) coincides with star 10, which is likely a cluster non-member. This star is located 6/6 from the cluster center, outside of the cluster radius (3/5). Its spectrum has CO bands at 2.29 $\mu$m, which indicate a late-type star.

We estimated the ratios between the X-ray and bolometric luminosities and compared the ratio, hardness, and X-ray luminosities of our nine X-ray emitters with those of Chandra point sources detected in Westerlund 1 (Figure 5, Clark et al. 2005b). In Westerlund 1, WR stars have luminosities $L_X$ larger than $10^{32}$–$10^{34}$ erg s$^{-1}$ and hardness from $-0.1$ to $1$, while most of the detected OB stars have $L_X = 10^{32}$ erg s$^{-1}$ (which is consistent with a ratio of $\sim 10^{-7}$) and hardness between $-0.8$ and $-0.1$, as expected for single stars with shocked winds. Clark et al. suggest that all OB stars with X-ray emission significantly harder than $-0.5$ in Westerlund 1 are binary systems. This conclusion is supported by emerging evidence of a high-binary fraction of massive stars in Westerlund 1 (Bonanos 2007). Skinner et al. (2010) propose a number of other possible scenarios to explain the X-ray emission of single WN stars. Magnetic wind confinement could also explain the presence of a hot plasma component without invoking the presence of a close companion. However, current detections of magnetic fields in WN stars are absent.

Star 4, a WN7 star, is the brightest X-ray emitter. It is associated with the Chandra source 24 (Helfand et al. 2007) and coincides also with the XMM source 24 (Helfand et al. 2007). The ratio between the X-ray and bolometric luminosities of star 4 is $3.7 \times 10^{-7}$. For star 7, we obtained a ratio seven times fainter. Both ratios are consistent with those measured in other WN stars by Skinner et al. (2010). Their high values of hardness (0.78 and 0.89 in Table 3) are consistent with those of colliding wind binaries (Clark et al. 2008). Since only a few other late WN stars have been detected in X-ray (Skinner et al. 2010), our new detections are a significant addition.

Star 5 (O7–O9) was detected by both the XMM and Chandra satellites (see Table 3). It is a strong X-ray emitter ($L_X = 1 \times 10^{32}$ erg s$^{-1}$); the ratio between the X-ray and bolometric luminosities is $2.9 \times 10^{-7}$. Besides the two WR stars, star 5 is the only other source with a strong X-ray hardness (0.4). The high values of X-ray luminosity and hardness indicate that 5 is another binary.

For the BSGs 2 and 3 (B0–B3), we measured ratios between the X-ray and bolometric luminosities of (2.1–4.3) $\times 10^{-8}$, which are in agreement with the ratios measured for single stars later than B1 (Cohen 1996; Waldron & Cassinelli 2007). Stars 8 and 9 (O7–O9) have also a ratio of about $2.5 \times 10^{-8}$. For star 6, an O6–O7If, we estimated a ratio of $1.3 \times 10^{-8}$. The low ratio and low hardness ($-0.57$) suggest radiative shocks in stellar winds.

### 5. SPECTROPHOTOMETRIC DISTANCES

Massive evolved stars in a young stellar cluster span a range of masses (see Figure 7), and therefore of luminosities. Spectrophotometric distances from OB supergiants are less

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**Table 3**

| ID | $K_s$ (mag) | Sp. Type | ID$_{Ch}$ | Counts$_{Ch}$ | HR | ID$_{XMM}$ | Counts$_{XMM}$ | $L_X$ $(10^{31}$ erg s$^{-1}$) |
|----|-------------|----------|-----------|--------------|----|------------|----------------|-------------------------------|
| 2  | 7.22        | OB       | 39        | 14.10        | $-0.33$ | ... | ... | 4.1 |
| 3  | 7.79        | OB       | 43        | 16.40        | $-0.53$ | ... | ... | 4.8 |
| 4  | 7.94        | WR       | 24        | 272.40       | 0.78  | 2 | 238 | 80.5 |
| 5  | 8.56        | OB       | 41        | 214.50       | 0.42  | 4  | 138 | 63.4 |
| 6  | 8.57        | OB       | 58        | 13.60        | $-0.57$ | ... | ... | 4.0 |
| 7  | 8.66        | WR       | 37        | 34.90        | 0.89  | ... | ... | 10.3 |
| 8  | 8.75        | OB       | 27        | 13.00        | $-0.82$ | ... | ... | 3.8 |
| 9  | 9.34        | OB       | 36        | 9.50         | $-0.20$ | ... | ... | 2.8 |
| 10 | 9.60        | K        | 71        | 71.10        | $-0.31$ | ... | ... | 21.0 |

**Notes.** For each star, number designations, $K_s$ magnitudes, and spectral types from Tables 1 and 7 are followed by the number designations (ID$_{Ch}$), counts (counts), and hardness (HR) from the Chandra observations by Helfand et al. (2007), and by the number designations (ID$_{XMM}$) and XMM counts reported by Funk et al. (2007). Estimates of $L_X$ are taken from Paper I, and assume a distance of 4.7 kpc, $N(H) = 1.6 \times 10^{22}$ cm$^{-2}$, a power-law model, and a photon index of 1.5. X-ray luminosities are given in units of $10^{31}$ erg s$^{-1}$.
Figure 7. For a given age, the mass at the TO and the maximum mass predicted by models are shown. Several models are used: a model by Schaller et al. (1992) with a solar metallicity (asterisks), models with metallicity twice solar by Schaerer et al. (1993) (diamonds), models with high mass loss by Meynet et al. (1984) (triangles), and the rotating models by Meynet & Maeder (2000) (crosses). For each model, the maximum masses are connected with a dotted line, while the masses at the TO are connected with a dashed line. (A color version of this figure is available in the online journal.)

Figure 8. Luminosities of massive stars in the Cl 1813-178 cluster are plotted vs. effective temperatures. Values are taken from Table 2. Stellar tracks for stars of 20, 25, 40, 60, and 85 M☉, based on rotating Geneva models with a solar metallicity, canonical mass-loss rates, and initial rotational velocity of 300 km s⁻¹ are also shown with dotted, dashed, and continuous lines. For clarity, we use different line styles together with labels to indicate each model. (A color version of this figure is available in the online journal.)

Table 4. Average Spectrophotometric Distances

| Sp. Type | Distance  |
|----------|-----------|
| OB V     | 2.9 ± 0.8 |
| OB III/II| 3.8 ± 1.0 |
| WN7      | 4.2 ± 1.6 |
| Average  | 3.6 ± 0.7 |

accurate than those from dwarfs and giants. When considering the dwarfs and the MK magnitudes for O9, B0, B1, and B2 dwarfs (Martins & Plez 2006; Humphreys & McElroy 1984; Koornneef 1983), we estimated distances of 3.8 ± 0.6 kpc, 3.2 ± 0.5 kpc, 2.6 ± 0.4 kpc, and 1.9 ± 0.3, respectively.

From the photometric properties of the candidate giants (nos. 9, 21, 22, and 23) and MK values for classes II and III from Humphreys & McElroy (1984) and Wegner (1994), we derived an average spectrophotometric distance of 3.0 ± 0.7 kpc for class III or 4.5 ± 0.6 for class II.

For the two WN7 stars, we adopted intrinsic magnitudes from Crowther et al. (2005), and obtained a distance of 2.6 kpc for star 4 and 5.8 kpc for star 7. The average distance for the two WN7 stars is 4.2 ± 1.6 kpc.

The derived spectrophotometric distances are listed in Table 4. While the distance estimates from giants and WRs within errors are consistent with the kinematic distance, the distance estimates from dwarfs are only consistent with the kinematic distance if the dwarfs are all late-O stars. Higher-resolution spectra are needed to refine the spectral types.

Observations of radio hydrogen recombination lines of the W33 complex reveal two velocity components (Bieging et al. 1978; Goss et al. 1978). By using the radial velocity component at 35 km s⁻¹ and the rotation curve of Reid et al. (2009), we calculated a near kinematic distance of 3.53 ± 0.40 kpc, while we obtained a distance of 4.82 ± 0.38 kpc with the radial velocity component at 62 km s⁻¹. A radio monitoring program of methanol masers in the direction of the W33 complex is currently ongoing. It will yield parallactic distances of the masers (e.g. Reid et al. 2009; Brunthaler et al. 2011).

6. PROGENITOR MASSES AND THE CLUSTER AGE

The Cl 1813-178 cluster contains a large number of evolved massive stars (BSGs, a cLBV, two WN7 stars, and one RSG star), which are listed in Table 1. We plot the inferred stellar luminosities versus stellar effective temperatures in Figure 8, together with theoretical stellar models from the Geneva group (Meynet & Maeder 2000). By comparison with the models, we estimated initial masses from 20 to 100 M☉.

Models predict a large span of stellar masses in post-main-sequence phase, e.g., a population of 4.0 Myr would have a mass of 25–35 M☉ at a turn-off (TO), but it would still contain stars of about 50 M☉, or even 100 if rotating models are considered. This is well illustrated in Figure 7, where we show the predicted maximum initial masses and TO masses as a function of cluster age. We used non-rotating models by Schaller et al. (1992) and Schaerer et al. (1993), models with high mass loss by Meynet et al. (1994), and the rotating models by Meynet & Maeder (2000). Metallicity ranges from solar to twice solar. For the same age, different models predict variations in the initial masses of up to 50%.

The mixture of evolved stars indicates progenitor masses larger than 20 M☉, and more likely of 25–60 M☉, with a few exceptions.

The Of stars are among the most luminous stars. The luminosity of the O8–O9If star suggests an extremely massive star (100 M☉; Meynet & Maeder 2003). The O6–O7If star has an estimated L* = (8.1 ± 2.2) × 10⁵ L☉, which is predicted for 30–70 M☉.

WR stars of WN7 type have been found only in stellar clusters with masses at the TO larger than 35–40 M☉ (Massey et al. 2001; Clark et al. 2005a). The luminosities of the WR stars in the Cl 1813-178 cluster (L* = (5.2 ± 2.3) × 10⁵ and (4.5 ± 1.9) × 10⁵ L☉) are similar to those inferred for WN7 stars in the Westerlund 1 cluster (L* from 3.1 × 10⁵ to 5.0 × 10⁵ L☉). The stellar luminosities suggest initial masses from 40 to 70 M☉.
The cLBV and RSG have luminosities expected for less massive stars ($\sim 20 M_\odot$). However, the 2MASS magnitudes of the RSG star have errors of about 0.3 mag, due to saturation, and the resulting luminosity could be underestimated.

Models of young simple stellar populations by Meynet & Maeder (2003) predict that stars with masses between 9 and 25–35 $M_\odot$ have an RSG phase. Single WR stars have initial masses greater than 26–30 $M_\odot$, while binary WR stars have initial masses greater than 20–25 $M_\odot$ (Eldridge et al. 2008). By assuming coevality between the RSG and the WR stars, the Cl 1813-178 cluster would be between 4 and 6 Myr old. A cluster with stars exceeding 100 $M_\odot$ (like the O8–O9I) would require an age of 3–4 Myr, and a TO at 35 $M_\odot$. Therefore, the simultaneous presence of RSGs, WRs, and Of stars would further narrow the possible age range to 4–4.5 Myr. However, either the luminosities of the cLBV, of the RSG star, and/or of the late-B supergiant are underestimated by ~0.7 dex, or the “cluster” is more of an “association” with some degree of non-coevality.

The cLBV star appears to be rather faint. The estimated luminosity of $2.4 \times 10^3 L_\odot$ is similar to that of the HD168607 and HD316285 LBVs (Clark et al. 2005a). Other known LBVs in clusters are typically among the most luminous, e.g., qF362 and the pistol star in Quintuplet (e.g., Mauerhan et al. 2010). In Westerlund 1, the W243 LBV has an initial mass of about 40 $M_\odot$, which is consistently similar to the masses of the cluster WRs (40–50 $M_\odot$), and larger than the estimated mass at the TO (30 $M_\odot$) (Ritchie et al. 2009). The cLBV in Cl1813-178 has a mass smaller than that of the two detected WR stars. Its mass is consistent with the mass of the RSG and would require a mass at the TO of about 20 $M_\odot$ and an age of 5–7 Myr. Further observations are recommended to explore the degree of coevality in Cl1813-178. Some non-coevality would easily explain the discrepant masses. A population with an age of 4.0–4.5 Myr, and a spread in age of 1 Myr, could explain the observed range of stellar masses.

The stellar mass at the TO for a population with an age of 4.0–4.5 Myr is likely between 25 and 35 $M_\odot$. This is consistent with the observations of dwarfs and giants. Three OB dwarfs with $K_s < 10.0$ mag were detected with O9–B3 spectral types, while the giants with O7–B3 types have $K_s = 9.3–9.5$ mag. An O7V star (~32 $M_\odot$) at an average extinction of $A_K = 0.8$ mag and a distance of 4.8 kpc is expected to have a $K_s \simeq 10.4$ mag (Martins & Plez 2006), while an O9V (~22 $M_\odot$) star has a $K_s = 10.9$ mag.

A further spectroscopic survey of fainter stars is needed to sample the TO region. Moreover, high-resolution spectra would allow for a more precise spectral classification. By narrowing the errors shown in Figure 8, and increasing the sample, we will be able to better constrain the age and verify the degree of coevality.

7. THE CLUSTER MASS

By adding the masses of the spectroscopically identified massive stars, we estimated a minimum cluster mass of 990 $M_\odot$. We considered all 34 stars with $J - K_s$ between 1 and 3 mag and $K_s < 10$ mag. By assuming that they all have masses greater than 35 $M_\odot$, and using a Salpeter mass function integrated from 0.8 to 120 $M_\odot$, we estimated a cluster mass of 13,000 ± 3000 $M_\odot$, where the error is the Poisson error of the number of massive stars. By assuming that these 34 stars have masses greater than 25 $M_\odot$, we obtained a cluster mass of 8700 ± 2000 $M_\odot$. The two calculations take into account the uncertainties of the mass at the TO (25–35 $M_\odot$), predicted for a coeval population with an age of 4–4.5 Myr.

The Cl 1813-178 cluster is therefore, a new addition to the list of 13 known young massive clusters ($\geq 10^4 M_\odot$) in the Milky Way (Messineo et al. 2009; Negueruela et al. 2010).

8. CLUSTER SURROUNDINGS

A 24 $\mu$m image from MIPS-GAL, the survey of the inner Galactic plane using the Multiband Infrared Photometer for Spitzer aboard the Spitzer Space Telescope (Carey et al. 2009), of the whole W33 region is shown in Figure 9, together with contours of radio continuum emission from MAGPIS (White et al. 2005). The complex extends over an area of roughly 25′ × 20′ (Bieging et al. 1978). Radio observations show that W33 is made up of a number of discrete sources. Some of these radio sources have been classified as candidate SNRs by Brogan et al. (2006) and Helfand et al. (2006) on the basis of morphology and spectral indices, with MAGPIS data (White et al. 2005). See Table 6.

The Cl 1813-178 cluster appears located on the edge of the W33 complex. The radial velocity of the K2I star in the Cl 1813-178 cluster is 62 ± 4 km s$^{-1}$ (Paper I) and well agrees with the high-velocity gas component of W33 (Dame et al. 2001). The spatial coincidence of the Cl 1813-178 cluster with the SNR G12.82-0.02 and G12.72-0.00 has already been reported in Paper I and supports the association of the cluster with the complex. The filamentary shape of the Cl 1813-178 stellar cluster and its location on the edge of W33 suggest a secondary episode of star formation, perhaps triggered by an expanding shell.

We searched for other possible candidate clusters and associations with SNRs in the direction of the W33 complex. A number of candidate stellar clusters have been identified in GLIMPSE and 2MASS images in the direction of the W33 region by Mercer et al. (2005) and Bica et al. (2003), which we list in Table 5. The W33 MYSO (Davies et al. 2010) is projected...
into SNR6 (G13.1875+0.0389; Helfand et al. 2006). The spatial coincidence of the SNR and the MYSO suggests a physical association. The W33A MYSO could be an episode of triggered star formation induced by a supernova explosion. Mercer1 candidate cluster is the object number 1 in the list of Mercer et al. (2005). It was identified as a stellar overdensity in the GLIMPSE catalog with an automatic algorithm. It is located at the center of the molecular complex, and it appears as a spread overdensity. Two other candidates are reported in literature in the surrounding of the W33 complex, but without a clear connection with the W33 complex. The BDS2003-115 candidate cluster is about 20’ North of the main W33 complex and is associated with SNR5 (G12.83-0.02; Helfand et al. 2006). The BDS2003-7 candidate cluster appears as a small group of stars without associated radio emission (Bica et al. 2003).

We visually inspected the 2MASS images and located two other clumps of stars (cl1 and cl2). The cl1 candidate appears as a group of point sources on bright nebular emission in the 2MASS K_s image. Inspection of the GLIMPSE and MAGPIS images reveals the presence of an H II region, suggesting the presence of massive stars (see Table 5 and Figures 10 and 11). The cl2 candidate is another small concentration of bright stars (K_s = 8–10 mag) in another H II region. Nothing is reported in previous literature about both, cl1 and cl2, clumps. In addition, we searched for stellar overdensities in the direction of the W33 complex using both 2MASS and GLIMPSE star counts. Detections are hampered by strong variations of the background level, which are due to variations of interstellar extinction and nebular emission. A spectroscopic and photometric follow-up study of these regions with SINFONI and UKIDSS data is ongoing, in order to confirm the presence of massive stars.

Near-infrared spectroscopic follow-up observations are needed to characterize these sources and to confirm their association with the W33 complex. However, the associations of Cl 1813-178, cl1, and cl2 with H II regions and/or SNRs suggest that these are other condensations of massive stars in the W33 complex.

### 9. SUMMARY

A near-infrared spectroscopic survey of the brightest stars in the direction of the Cl 1813-178 cluster is presented. Among the 61 observed stars, 25 massive stars were detected. Two WR stars of type WN7, a cLBV, and 21 OB stars were identified. Among the OB stars, an O8–O9If star and an O6–O7If star were discovered. Eight of these evolved stars also have X-ray emission, as detected by the Chandra and XMM satellites. The hardness of the X-ray emission from the two WN7 stars strongly suggests binary systems.

A spectrophotometric analysis of the OB stars reveals 14 supergiants, 4 giants, and 3 dwarfs. From the giants, dwarfs, and WRs, we derived average spectrophotometric distances of 3.8±1.0 kpc, 2.9±0.8 kpc, and 4.2±1.6 kpc. The distances from giants and WRs are in agreement with the kinematic distance. The distance estimates from dwarfs are only consistent with the kinematic distance if the dwarfs are late-O stars.

The mixture of evolved massive stars is reminiscent of other Galactic young massive clusters, such as Westerlund 1, Quintuplet, Galactic center, and Cl 1806-20. We estimated stellar luminosities, and therefore masses, by comparing the luminosities with evolutionary tracks from the Geneva group. By assuming a Salpeter mass function, we obtained a cluster mass of (1.0±0.2)×10^6 M☉. A likely cluster age of 4–4.5 Myr is derived; however, a spread in age of about 1 Myr cannot be excluded. In order to better constrain the degree of coevality, further spectroscopic observations are required.

The Cl 1813-178 cluster is located on the Western edge of the W33 complex. We have located several other candidate stellar clusters that could belong to the same complex.

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### Table 5

| ID     | R.A.  | Decl. | Radius (’) | References                        |
|--------|-------|-------|------------|-----------------------------------|
| Cl 1813-178 | 18 13 24 | −17 53 31 | 3.5 | Paper I                           |
| Mercer1 | 18 13 57 | −17 56 46 | 2.3 | Mercer et al. (2005)              |
| BDS2003-115 | 18 14 05 | −17 28 29 | 1.2 | Bica et al. (2003)                |
| BDS2003-7  | 18 10 55 | −17 41 25 | 0.6 | Bica et al. (2003)                |
| cl1     | 18 14 22 | −17 56 10 | 1.8 | Present work                      |
| cl2     | 18 14 08 | −18 00 15 | 1.0 | Present work                      |

### Table 6

| ID | Name        | R.A.  | Decl. | Radius (’) | References                        |
|----|-------------|-------|-------|------------|-----------------------------------|
| SNR1 | G12.26+0.30 | 18:11:17 | −18:10:00 | 4 | Brogan et al. (2006); Helfand et al. (2006) |
| SNR2 | G12.58+0.22 ? | 18:12:14 | −17:55:00 | 5 | Brogan et al. (2006) |
| SNR3 | G12.72-0.00 | 18:13:18 | −17:55:42 | 4 | Brogan et al. (2006); Helfand et al. (2006) |
| SNR4 | G12.83-0.02 | 18:13:35 | −17:50:30 | 2 | Brogan et al. (2006); Helfand et al. (2006) |
| SNR5 | G13.1875+0.0389 | 18:14:07 | −17:28:43 | 2.5 | Helfand et al. (2006) |
| SNR6 | G12.9139-0.2806 | 18:14:44 | −17:52:47 | 1.5 | Helfand et al. (2006) |
Figure 10. 2MASS $K_s$ images of the BDS2003-115 cluster (top left), the BDS2003-7 cluster (top middle), the cl1 cluster (top right), the cl2 cluster (bottom left), and the Mercer1 cluster (bottom middle).

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

Figure 11. Composite images of SNR5, SNR6, cl1, cl2, and Cl 1813-178. In blue the GLIMPSE 3.6 $\mu$m, in green the 5.8 $\mu$m, and in red the 8.0 $\mu$m are shown. Overplotted are contours of 90 cm radio continuum emission detected by MAGPIS (White et al. 2005).

(A color version of this figure is available in the online journal.)
discussion on parallactic distances to the W33 complex using methanol masers. We acknowledge helpful comments and suggestions by an anonymous referee.

APPENDIX A

LATE-TYPE STARS

The EW(CO)\(_s\) can be used for classification in subclasses of late-type stars. There is a linear correlation between stellar effective temperatures and EW(CO)\(_s\) of the CO bands. Furthermore, since giants and supergiants follow two different relations, information on the luminosity class can also be obtained (see, e.g., Figer et al. 2006; Davies et al. 2007).

Among the observed 60 stars, 37 are found to be late-type stars. For 36 of them, spectra were taken with the K-long grism, covering the region of the CO band head at 2.29 \(\mu\)m. CO bands at 2.29 \(\mu\)m in absorption are detected in all spectra. Star 55 was observed only with the K-short grism; however, the presence of Na lines (at 2.2075 and 2.2077 \(\mu\)m) and Mg I at 2.11 \(\mu\)m suggests a spectral type later than G0.

The equivalent widths of 32 of these late-type stars are compatible with that of giant stars with spectral type from K0III to M7III (Table 7). For star 58 we do not report any spectral type, since its spectrum has a poor signal to noise.

Star 32, 38, and 39 have EW(CO)\(_s\) typical of RSG stars, with spectral types M2.5, M3.5, and M1, respectively. However, their photometric properties indicate that they are unrelated to the stellar cluster. Star 1 is consistent with being a K2–K5I cluster member (see Paper I).

Young massive clusters with ages from 4 to 30 Myr may contain yellow supergiants (YSG) stars, e.g., the Westerlund 1 (Clark et al. 2005a) and RSGC1 clusters (Figer et al. 2006). YSG are rare F- or G-type supergiants in transition toward the RSG phase or, back from the RSG locus, evolving blueward. In a coeval population, YSGs or RGB stars are expected to be brighter in \(K\) than early-type massive stars. In the Cl 1813–178 cluster, all detected stars with CO band head at 2.29 \(\mu\)m appear fainter than the brightest OB stars, and the gap between the brightest early-type star (\(K = 6.667\) mag) and the K2I star (\(K = 3.79\) mag) is devoid of stars. Furthermore, the CO band heads of the five late-type stars with \(K\) between 7 and 8 mag indicate late-M giants (M2–M5), or late-K supergiants (K2–K4). Their EW(CO)\(_s\) are not consistent with being F or G supergiants.

Table 7

| ID | R. A.    | Decl. | B  | V  | J  | H  | Ks | B–V | [3.6] | [4.5] | [5.8] | [8.0] | Tel.  | Sp |
|----|----------|-------|----|----|----|----|----|-----|-------|-------|-------|-------|-------|-----|

Notes. For each star, number designations and coordinates (J2000) are followed by magnitudes measured in different bands. B, V, and \(K\) measurements are from 2MASS, while the magnitudes at 3.6 \(\mu\)m, 4.5 \(\mu\)m, 5.8 \(\mu\)m, and 8 \(\mu\)m are from GLIMPSE. B, V, and R associations are taken from the astrometric catalog NOMAD.

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In order to estimate stellar luminosities, estimates of effective temperatures and bolometric corrections as a function of spectral type need to be known. Since an homogeneous calibration extending from O stars down to early A stars is missing, we summarize all the adopted values in Tables 8–11.

For O-type stars, we used the $T_{\text{eff}}$ values given by Humphreys & McElroy (1984). For early-B supergiants, we adopted the $T_{\text{eff}}$ from Martins et al. (2005).

For late-B and A supergiants, those by Humphreys & McElroy (1984). For B giants, we
adopted the $T_{\text{eff}}$ by Humphreys & McElroy (1984). For B and A dwarfs, we used $T_{\text{eff}}$ estimated by Humphreys & McElroy (1984) and Johnson (1966).

For O-type stars, we used the bolometric corrections in $K$ band ($BC_K$) by Martins & Plez (2006). For early-B-type stars, we used those provided by Bibby et al. (2008). We estimated the $BC_K$ of late-B supergiants and giants by assuming bolometric corrections in the $V$ band ($BC_V$) from Humphreys & McElroy (1984), and intrinsic $V - K$ colors from Koornneef (1983) and Wegner (1994). For dwarf stars, a set of homogeneous $BC_K$ was obtained by interpolating an isochrone of 0.5 Myr and solar metallicity from Lejeune & Schaerer (2001) at the assumed effective temperatures (Humphreys & McElroy 1984; Johnson 1966).

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Table II

| Sp | $T_{\text{eff}}$ | $BC_K$ | $J - K$ | $H - K$ | References |
|----|----------------|--------|---------|---------|------------|
| K2I | 4015 | +2.5 | +0.65 | +0.13 | Levesque et al. (2005), Koornneef (1983) |
| M1I | 3745 | +2.7 | +1.00 | +0.22 | Levesque et al. (2005), Koornneef (1983) |
| M2.5I | 3615 | +2.8 | +1.06 | +0.27 | Levesque et al. (2005), Koornneef (1983) |
| M3.5I | 3550 | +2.9 | +1.16 | +0.28 | Levesque et al. (2005), Koornneef (1983) |
| WN7a | −3.9 | +0.13 | −0.11 | Crowther et al. (2006a) |
| WN7b | −3.5 | +0.37 | +0.27 | Crowther et al. (2006a) |

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