Near-infrared Spectroscopy of Ultracompact H II Regions in W51A with NIFS/ALTAIR*

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Abstract

W51A is the most active star formation region of the giant H II region W51. It harbors the two massive protoclusters W51e and W51 IRS2, which are very rare in the Galaxy. We aim to identify the newborn massive stars and ultracompact H II regions to derive its distance and age. We performed Integral Field Unit observations with NIFS + ALTAIR of nine targets in the W51A subregion. The distance modulus was obtained using the spectral classification in the K band and a reddening law appropriate to the inner Galactic plane. We derived the distance and the spectral types for five of the targets, ranging from O8 to O9.5, similar to those derived from radio continuum data, except for two sources to which we assigned a somewhat later spectral type. We included another seven objects with precise spectral classification from other works, which allowed us to better constrain the distance estimate. Our spectrophotometric distance \( d = 4.80 \pm 1.27 \text{ kpc} \) is in good agreement with those derived from the Galactic rotation model and trigonometric parallaxes, placing the region near the tangent point of the Sagittarius arm. We conclude that the stars studied in this work have an age spread of 1.5–4 Myr, substantially older than thought to date.

Unified Astronomy Thesaurus concepts: Massive stars (732); Star forming regions (1565); Spectroscopy (1558); Stellar spectral lines (1630); Stellar spectral types (2051); Near infrared astronomy (1093); Spectrophotometry (1556)

1. Introduction

W51 is a massive star-forming complex located near the tangential point of the Carina–Sagittarius arm, which has a kinematic distance of 5.5 kpc (Kolpak et al. 2003). Due to its location and its vantage point, the distance to W51 is a matter of discussion (e.g., Figeruêrêdo et al. 2008). The complex actually comprises the entire W51 giant molecular cloud (GMC) fragmented into four main clusters: G49.58—0.38, G49.50—0.4 (also known as W51 North and W51A; hereafter W51A), G49.2—0.3, and G48.9—0.3. The W51 complex is one of the most intense infrared sources in the sky (Kumar et al. 2004), and may represent a local case of the starburst phenomenon. For this reason, the complex has been the subject of recent multiwavelength studies in the near-infrared (Bik et al. 2019), mid-infrared (MIR, Barbosa et al. 2016; Lim & De Buizer 2019), submillimeter (Ginsburg et al. 2016a), and radio wavelengths (Ginsburg et al. 2016b).

The clusters within the W51 GMC show evidence of ongoing massive star formation at different rates. W51A is the youngest and the most active cluster (Okumura et al. 2000; Bik et al. 2019), with a large number of ultracompact (UC) H II regions identified by Mehringer (1994) and Ginsburg et al. (2016b). The stellar population of W51A was studied by Okumura et al. (2000) and Kumar et al. (2004), and by Figuerêrêdo et al. (2008) who spectroscopically identified four O stars (within the range O4–O7.5). More recently, Bik et al. (2019) reported the identification of another four late O/early B stars in this cluster based on the analysis of NIR spectroscopy.

Lim & De Buizer (2019) presented a study of the regions W51A and G49.4–0.3 with unprecedented details in the MIR (at 20 and 37 \( \mu \text{m} \)), confirming the very young nature of both clusters. In their study, 47 pointlike sources in the MIR were identified as massive young stellar objects (MYSOs), but only 21 were confirmed as the counterparts of radio sources identified by Mehringer (1994) and Ginsburg et al. (2016b). According to the latter authors, the fact that more than 50% of their sample is still radio-quiet indicates that the majority of the MYSOs in W51 have not reached the UC H II phase yet, placing them at even earlier evolutionary phases, such as hypercompact (HC) H II regions or even hot cores (Churchwell 2002).

The present work concentrates on the investigation of nine UC H II regions within W51A, and the paper is organized as follows. Section 2 describes the details of the observational procedures and the data reduction. In Section 3 we present the spectroscopic results and classification of the NIR sources, including, where appropriate, previous information already published and so available to us. In Section 4 we present a new spectrophotometric distance to W51A, and in Section 5 we discuss our results, comparing them with previous works. Finally, we summarize our conclusions in Section 6.
2. Observations and Data Processing

2.1. Target Selection and Observations

The sources observed in this work were selected among the brightest UC H II regions within W51A, observed with the Very Large Array at 6 cm by Mehringer (1994). The 6 cm map was matched with the 3.6 μm image taken with the Spitzer/IRAC camera (Fazio et al. 2004) to identify NIR counterparts of the UC H II regions presented by Barbosa et al. (2016), using a maximum 3″ offset between the radio and the IR positions. Figure 1 is a NIR image of W51A showing the targets studied in this work. Finally, the position of the NIR counterparts was refined using the JHK$_S$ images from the UKIDSS Galactic Plane Survey (Lucas et al. 2008). Table 1 presents the details of UC H II regions and the NIR counterparts identified in the procedure described above.

The UC H II regions studied in this work are labeled and indicated by the yellow circles. The map corresponds to a field of view of 8′ × 8′, centered at R.A. = 19:23:40.0, decl. = +14:30:51 (J2000).

![Figure 1](image_url)

Figure 1. False-color near-infrared image of the W51 North region. The image is color-coded as red (K band), green (H band), and blue (J band) from the UKIDSS Survey (Lawrence et al. 2007), overlaid by the 6 cm radio emission contours from Mehringer (1994). The contours are placed at 5$^n$ level (n = 1, 2, 3, ...). The UC H II regions studied in this work are labeled and indicated by the yellow circles. The map corresponds to a field of view of 8′ × 8′, centered at R.A. = 19:23:40.0, decl. = +14:30:51 (J2000).

Table 1

| UC H II Region | Spectral Typea | Designation | K$_S$ (mag) | Obs. Date (UTC) | Exp. Time (s) | Spatial Res. (arcsec) |
|---------------|---------------|-------------|-------------|----------------|--------------|----------------------|
| W51a          | O6            | J192329.67+143135.0     | 10.81       | 2015-06-30     | 400          | 0.17                 |
| W51b$_1$      | O8.5          | J192334.72+143205.2     | 11.77       | 2015-06-30     | 800          | 0.21                 |
| W51b$_2$      | B0            | J192335.88+143128.8     | 12.06       | 2015-07-01     | 800          | 0.25                 |
| W51c$_1$      | O5            | J192341.03+142927.0     | 11.64       | 2015-06-30     | 800          | 0.18                 |
| W51c$_2$      | B0.5          | J192344.79+142911.2     | 12.75       | 2015-07-01     | 1750         | 0.17                 |
| W51e$_1$      | O9            | J192343.93+143027.8     | 14.56       | 2015-07-03     | 1800         | 0.19                 |
| W51e$_2$      | O9.5          | J192342.28+143033.0     | 11.36       | 2015-06-30     | 400          | 0.20                 |
| W51g          | O6            | J192350.45+143257.4     | 9.85        | 2015-06-30     | 50           | 0.23                 |

Note.

a After revising the spectral types derived by Mehringer (1994) from radio continuum flux according to the calibration tables presented by Martins et al. (2005).
of $3'' \times 3''$ (McGregor et al. 2003). The adaptive optics (AO) module ALTAIR was used during the observations in laser guide star mode to correct the image of sources for the distortion of the Earth’s atmosphere (Saddlemyer et al. 1998). The image quality of the AO-corrected observations was estimated based on the full width at half maximum (FWHM) of an image of a nearby area of blank sky. The typical spatial resolution of the images was obtained by averaging the FWHM of each source, excluding those that exhibit extended emission (sources W51b1 and W51e7, see Sections 3.3.3 and 3.3.5) and W51e7 due to the low signal-to-noise ratio of the image. The typical spatial resolution is about 0.0'20 (0.27 pc at the new derived distance, see Section 3).

The data were obtained in the $K$ band (NIFS grating “Z” and filter “HK”), providing an effective spectral coverage over $1.99 \mu m \leq \lambda \leq 2.40 \mu m$ (central wavelength of $\lambda_c = 2.20 \mu m$). For each on-source observation (position A), we took an associated image of a nearby area of blank sky (position B), offset by $\sim 10''$ from the target. This last image was used to subtract sky emission lines, mainly OH lines from airglow in the atmosphere, during the data reduction process. As the OH emission lines vary on timescales as short as a few minutes, the maximum individual exposure time was set to 400 s. For the faint sources that required multiple exposures, we adopted an observation strategy between object and sky images following a template for each science target, matching the airmass of the science observations. This star was selected as a template to correct for the telluric absorption lines. The data reduction process is fully described in the next section.

2.2. Data Reduction

The standard data processing of NIFS observations was performed using the Gemini/NIFS IRAF package. Calibration data were prepared with Gemini-IRAF NFPREPARE task, which adds the data quality and variance extensions to each FITS file.

A flat-field template was created using the set of flat-on and flat-off images. The wavelength transformation was performed using the Ne–Ar lamp spectrum. The rms of the wavelength solution was $\leq 0.15 \AA$ for each slit. The spatial rectification model was made using a Ronchi mask image (for more information, see Blum & McGregor 2008).

The telluric and science observations were flat-fielded, wavelength-corrected, and sky-subtracted. The spectral template of the telluric lines was created by the extraction of a one-dimensional spectrum from a $0.5''$ radius aperture centered on the telluric standard star. Then, the stellar Brγ feature was removed by fitting a Voigt profile between two continuum points. Next, the telluric correction was applied to both science and sky images using the NTFELLURIC task.

Finally, the data cube was created by resampling the original rectangular spatial pixels to squared pixels of 0''05 in both $x$- and $y$-directions. At the end of the processing, final data cubes with dimensions of $\sim 60 \times 60$ spatial pixels and 2040 spectral pixels were delivered. A median-combined data cube was obtained from the input data cubes to suppress any bad pixels or possible cosmic rays present in the original data.

3. Results

The one-dimensional spectra of the object were extracted by performing a background subtraction of the spectrum of each source using a circular-annular aperture centered at the position of each object. Each spectrum was extracted through an inner radius of 4 pixels (0''20), from which was subtracted the background spectrum obtained through an outer radius of 7 pixels (0''35). After that, each spectrum was continuum-normalized by fitting a robust polynomial function of order $n = 4$ on line-free regions of the spectrum. The results are presented in Figures 2, 3, and 4.

We performed the spectral type classification of each source, first identifying photospheric lines using Peter van Hoof’s Atomic Line List and then comparing their normalized spectra with the atlasses presented by Hanson et al. (1996, 2005). We detected photospheric features in seven of the nine objects in our sample. Only nebular features were identified in the spectrum of W51e. We could detect no features in source W51e7 due to the low signal-to-noise ratio of its spectrum, so its analysis was inconclusive.

3.1. Stellar Spectral Classification of the NIR Counterparts of the UC H II Regions

3.2. Massive Stars

The continuum-normalized spectra of the NIR counterparts of the UC H II regions are presented in Figures 2, 3, and 4. The spectral features used for classification of the spectral types of the sources are labeled on the plots. When compared to the spectral types derived from radio continuum data, our classification led to similar spectral types (within uncertainties), except for objects W51a and W51c1. For these objects, we assigned a somewhat later spectral type. The extensive spectroscopic survey of UC H II regions conducted by Hanson et al. (2002) found a similar trend, when a direct classification was possible through photospheric lines. The individual analysis and the spectral classification of each source are presented below.

3.2.1. W51a

The spectrum of W51a is shown in Figure 2 (top). Several absorption features are observed in the spectrum of this object, including He(I(0–1) at 2.0581 $\mu m$, He(I(1–0) at 2.1137 $\mu m$, He II (7–10) at 2.1885 $\mu m$, and H(I(4–7) at 2.1661 $\mu m$ (Brγ)). A broad N III(7–10) emission is also observed at 2.1155 $\mu m$. N III emission is seen in spectra of stars earlier than O9, and considering that C IV emission is not detected in spectra of stars later than O7, as in the case of W51a, we can classify its ionizing source as an O8 star. Remaining emission lines in the W51c1 spectrum are artifacts introduced during the sky subtraction step.

3.2.2. W51b1

The spectrum of W51b1 is shown in Figure 2 (middle). This source exhibits the He(I(1–0) and Brγ in absorption.
These features suggest a spectral type between O9 and B2. Based on the intensity of these transitions, especially the profile of the He I line, we narrowed the spectral classification of this object to an O9.5 star. Additional narrow features in emission in the blue region of the spectrum are residuals from sky subtraction.
The spectrum of W51e leads us to classify this source as a MYSO, and W51e2 remains inconclusive. The spectrum of W51g exhibits only photospheric lines typical of low signal-to-noise ratio was smoothed by a factor of 3 in an attempt to identify any marginally detected photospheric line. The absence of photospheric features in the late-type stars, inconsistent with the NIR counterpart of a UC HII region (mass stars corrected for the heliocentric velocity. The vertical dotted lines indicate typical photospheric lines used to determine the spectral type of massive stars during the sky subtraction step.

**3.2.3. W51b2**

The spectrum of the NIR counterpart of W51b2 (Figure 2, bottom) shows He I(0–1) and Brγ emission within a broad absorption profile. The analysis of the absorption features in the spectrum of W51b2 suggests that it is a late O/early B star; however, the detection of a weak absorption profile of He II (7–10) suggests that this object corresponds to an O9.5 star. Moreover, we see the emission component of the Brγ feature is double-peaked, as is evident in the inset.

**3.2.4. W51e1**

The spectrum of W51e1 is presented in Figure 3 (top) and shows the He I(1–0) and the Brγ features in absorption. These features are present in spectra of O9–B2 stars; however, the He I(0–1) is marginally detected, leading to a slightly earlier stellar type classification than that of W51b1 (O9.5). Thus, we classified this object as an O9 star.

**3.2.5. W51e7**

The spectrum of source e7 is presented in Figure 3 (middle) and exhibits He I in absorption and a relatively broad Brγ absorption. The presence of these features suggests that the spectral classification is between O9 and B2, but based on the intensity of both features, we classified this object as an O9.5 star. It is important to note that W51e7 corresponds to object #7 in the study of Bik et al. (2019) and they classified this object as a B1 star.

**3.2.6. W51e1**

The spectrum of W51e1 is shown in Figure 3 (bottom). The only feature detected in the spectrum of W51e1 corresponds to the Brγ line in absorption, which on its own is not sufficient to provide any constraint on the stellar type classification of the source. Since we identified this source as the NIR counterpart of a UC H II region, we assigned a lower limit to the spectral type of B3 for this object to account for ionizing radiation that produces the UC H II region.

**3.2.7. W51e**

The background-subtracted spectrum of source W51e does not show any photospheric lines, suggesting that it is still deeply embedded in its cocoon of gas and dust in the early stages of formation. Its spectrum is presented in Figure 4 (top). Emission lines in the W51e spectrum are artifacts introduced during the sky subtraction step.

**3.2.8. W51e2**

We present the spectrum of source W51e2 in Figure 4 (middle). The spectrum does not show any spectral feature even after we smoothed it by a factor of 3 in an attempt to increase its signal-to-noise ratio, after the background subtraction. Thus, the nature of W51e2 remains inconclusive.

**3.2.9. W51g**

The spectrum of the NIR counterpart of the UC H II region W51g is presented in Figure 4 (bottom). Several photospheric absorption features were identified in the spectral range, such as the NaI doublet at 2.2065 and 2.2089 μm, Ca I lines at 2.2217 and 2.2814 μm, Ca I and/or Si I at 2.2658 μm and 2.2630 μm, Fe I at 2.2351 μm, and Mg I at 2.2828 μm. Also, the first four 12CO bandheads were observed at 2.2935, 2.3227, 2.3525, and 2.3829 μm, as well as the 13CO bandheads at 2.3448 and 2.3739 μm. These features are not likely to be observed toward massive stars or MYSOs; they correspond to photospheric features typical of late-type stars and suggest a K7 star. Therefore, the object identified as the NIR counterpart of W51g...
cannot be the ionizing source of the corresponding UC H II region.

This object corresponds to source 4319847702260151680 in the Gaia DR2 catalog (Gaia Collaboration et al. 2018) and its distance is 2.11 kpc (Bailer-Jones et al. 2018). In fact, its continuum shows a negative slope toward longer wavelengths, indicating that this star is not subjected to the same extinction of the region and is a foreground star seen along the line of sight to W51g.

3.3. Properties of the UC H II Regions

In the following subsections we present a brief review of each UC H II region studied in this work, compiled from the literature.

3.3.1. W51a

W51a is resolved in a shell-like UC H II region with a diameter of \( \sim 1 \) pc (Mehringer 1994). Based on the timescale of the expansion of a Strömgren sphere, Okumura et al. (2000) estimated its age to be 0.7 Myr, and based on their NIR photometry, they suggest that its NIR counterpart is actually a double MYSO of spectral types O6 and B1. Our results show that W51a is ionized by an O8 star. The difference may be explained by the environment surrounding the UC H II region, which may impact the expansion rate of the Strömgren sphere.

W51a has a remarkably different morphology at longer wavelengths, as recently shown by Lim & De Buizer (2019). Despite no pointlike counterpart identified at \( \lambda > 8 \) \( \mu m \), the source exhibits an irregular multipeaked morphology at \( 8 \) \( \mu m \), and shows a round shape at 20 \( \mu m \) and 30 \( \mu m \), brighter at the top and crossed by a dark lane on its equatorial region.

3.3.2. W51b1

The UC H II region W51b1 is not detected at \( \lambda = 3.6 \) cm, but has a diffuse morphology at \( \lambda = 6 \) cm, and exhibits a shell-like structure at \( \lambda = 20 \) cm with a linear diameter of less than 1 pc (Mehringer 1994). Okumura et al. (2000) classified the embedded source as an O9 star, and they estimated its age to be 0.8 Myr based on the expansion of a Strömgren sphere. Our results show that W51b1 is ionized by an O9.5 star in good agreement.

Spitzer/IRAC images at 6 and 8 \( \mu m \) exhibit a pointlike source and an arc-like feature surrounding it, with a diameter significantly smaller than that measured at 20 cm (20" and 25"), respectively. This arc-like structure is not observed at \( \lambda = 20 \) \( \mu m \), but it clearly appears at \( \lambda = 37 \) \( \mu m \), giving a comet-like morphology to this source (Lim & De Buizer 2019).

3.3.3. W51b2

Okumura et al. (2000) classified the ionizing source of W51b2 as a B1 star, with an estimated age of 0.2 Myr. Our results show that W51b2 is ionized by an O9.5 star also, in good agreement. The Spitzer/IRAC maps presented by Barbosa et al. (2016) exhibit W51b2 off-centered from its surrounding MIR emission. SOFIA observations presented by Lim & De Buizer (2019) exhibit this object as an unresolved pointlike source at 20 \( \mu m \), but extended at 37 \( \mu m \).

The UC H II region W51b2 is a shell-like source at 6 and 20 cm, with no 3.6 cm counterpart (Mehringer 1994). A similar inner He I and outer Br\( \gamma \) shell-like morphology is observed in the NIFS field of view, and we show the line maps of source b2 in Figure 5. The NIR continuum emission does not exhibit any extended emission associated with the NIR counterpart of the UC H II region. A secondary pointlike object is offset by \( \sim 1\prime\prime \) to the SW of the main source; however, the signal is too weak to detect any photospheric features associated with it.

The Br\( \gamma \) emission feature observed in W51b2 (Figure 2, inset) can be produced by either a disk (e.g., Blum et al. 2004) or an expanding shell of gas (see Hartmann et al. 2004 and references therein), as appears to be the case (see below). We measured its peak-to-peak velocity, \( \Delta v = 116.6 \) \( \text{km s}^{-1} \) (FWHM of the Gaussian profile of 179.4 \( \text{km s}^{-1} \)) and its velocity shift from rest wavelength \( v = (9.3 \pm 6.0) \) \( \text{km s}^{-1} \); all values corrected to the heliocentric velocity \( v_{\text{helio}} = 6.5 \) \( \text{km s}^{-1} \).

Both the extended He I and Br\( \gamma \) morphologies are very similar to that observed in the radio continuum map at 6.2 cm, showing a shell-like structure with FWHM of \( \sim 2\prime\prime \), which seems to be the outer layer of the structures identified in the NIFS maps. The emission of the He I transition exhibits a spherical structure, showing stronger emission to the N of the NIR pointlike source. The structure is nearly spherical with a FWHM of about \( 1\prime\prime \). The Br\( \gamma \) emission exhibits a slightly different morphology, showing a “mushroom-like” structure oriented in the N–S direction. The contrast of the Br\( \gamma \) intensity is similar to that of the He I, exhibiting a stronger emission to the N. The FWHM of the emission is larger than that probed by the He I, 2\( \prime\prime \), suggesting the ionized hydrogen is located in a layer further out than the extended neutral helium emission.
Figures 6 and 7 present the velocity maps of the He I and Brγ lines, respectively, for W51b2. Both maps are compatible with the scenario derived from the emission line maps from Figure 5, in which an inner bubble of the slowly expanding shell of He I is closer to the central star and is surrounded by a larger faster-expanding shell of ionized hydrogen.

3.3.4. W51c1

Source W51c1 appears as an arc-like UC H II region surrounded by extended emission at radio wavelengths. The arc-like emission feature is also seen in the Spitzer/IRAC images reported by Barbosa et al. (2016), and in 20 μm and 37 μm SOFIA maps from Lim & De Buizer (2019). A bow-shaped structure is more evident at 3.6 cm (Mehringer 1994).

Okumura et al. (2000) estimated the age of this source as 0.4 Myr. Based on their NIR photometry, these authors suggest that three sources (O5 + O6 + B0) are actually responsible for the ionization of the region; however, our results show that the ionizing object is an O9 star. The NIR counterpart of W51c1 corresponds to source #64 in the analysis presented by Figuerêdo et al. (2008), but those authors did not specifically associate the object to the UC H II region in their work.

3.3.5. W51e7

Source W51e7 was observed for the first time by Mehringer (1994), who classified it as a UC H II region. According to its 6 cm emission, this UC H II region is powered by a B1 star (Mehringer 1994; Barbosa et al. 2016). Its NIR counterpart was identified in the K-band image presented by Figuerêdo et al. (2008) and in the IRAC/Spitzer images from Barbosa et al. (2016). According to the NIR data presented by Okumura et al. (2000), source e7 is a ~0.3 Myr B0 star. MIR images taken at 20 μm and 37 μm show e7 as an unresolved source (Lim & De Buizer 2019). These prior classifications based on emission characteristics can be compared to the somewhat hotter spectral classification of O9.5V presented here.

The NIFS observations were able to resolve the K-band emission in the inner 3″ × 3″ region around the ionizing source of the UC H II region. We present the emission line maps of W51e7 in Figure 8. The He I emission exhibits a shell-like
structure, with FWHMs of $\sim 2''/4$ and $2''/2$ in the major and minor axes, respectively. The $\text{Br} \gamma$ emission has a spherical shape with FWHM larger than $\sim 2''/5$, fitting the entire field of view.

It is interesting to note that, in spite of its shell morphology, the inner He I emission bubble is more intense to the S, forming an arc-shaped structure, which is also observed in the radio continuum map. The distribution of the ionized hydrogen gas probed by the $\text{Br} \gamma$ emission does not exhibit the arc-shaped structure, but it shows a bright spot to the W, which also coincides with a peak in the radio emission.

The features revealed in the helium line map are also seen in the velocity maps of He I and Br$\gamma$ presented in Figures 9 and 10, respectively. The He I shell, centered on the NIR continuum source, is clearly seen at $v = -13.7 \, \text{km s}^{-1}$ and the arc-shaped structure is evident in the $50 \, \text{km s}^{-1}$ channel in Figure 9. The channel maps of the Br$\gamma$ emission exhibit the bright spot to the W of the pointlike object, but also indicate two fainter spots to the NE and SE of the source at $v = -58.5 \, \text{km s}^{-1}$, suggesting an inhomogeneous shell of ionized gas around the source.

### 3.3.6. W51e$_1$

Source W51e$_1$ exhibits a cometary morphology at radio wavelengths (Mehringer 1994) and it is also identified in the 4.5 $\mu$m Spitzer/IRAC map presented by Barbosa et al. (2016), offset by $\sim 2''$ from the radio peak. No pointlike emission was identified in the NIR (Okumura et al. 2000), in high-resolution ground-based MIR images (Barbosa et al. 2016), or in MIR maps taken with SOFIA (Lim & De Buizer 2019). Probably this is due to the intense emission from IRS1 (Barbosa et al. 2016).

### 3.3.7. W51e

Source W51e is a large arc-shaped UC H II region with an extended radio emission spanning more than 50″. This region exhibits the most intense radio emission among all the objects in W51A (Mehringer 1994); based on the number of photons emitted in the Lyman continuum, Mehringer (1994) proposed that the ionizing source is a cluster of nine O4 stars, or five O8 stars (using the values for stellar fluxes presented by Martins et al. 2005). From NIR photometry, Okumura et al. (2000) proposed a recipe (or a stellar equation) for the ionizing cluster: $O4 + O5 + O6 + O8 + 2 \times B2$. According to the latter authors, this cluster must not be older than 0.7 Myr.

W51e is also the most luminous source of the whole complex in the infrared, which led Wynn-Williams et al. (1974) to identify this source as IRS1. As such, the NIR counterpart of W51e is unresolved in maps obtained at 7, 12.3, and 24.5 $\mu$m (Barbosa et al. 2016), and 20 and 37 $\mu$m (Lim & De Buizer 2019). The NIR counterpart of this UC H II region corresponds to source #45 in the study presented by Figuerêdo et al. (2008). It is interesting to note that the source #44—one of the four O-type stars identified by those authors (O5) in the main cluster—is offset by less than 5″ to the S of W51e.
3.3.8. W51e2

Sources W51e1 and W51e2 form a subcluster within the extended radio emission arising from W51e. Both sources are likely young embedded O-type stars and, together with IRS2, represent the main regions of ongoing star formation activity within W51A (Ginsburg et al. 2015).

The NIR counterpart of the HC H II region W51e2 was not identified by Okumura et al. (2000), but a pointlike object can be identified within the 3″ search radius in the K-band images from Figuerêdo et al. (2008) (source #145, about ~1″ from the e2 radio peak). High-resolution ground-based MIR observations taken with T-ReCS were unable to identify any emission toward W51e2 (Barbosa et al. 2016), while this object appears as an unresolved emission in SOFIA maps at longer wavelengths (Lim & De Buizer 2019).

3.3.9. W51g

Source W51g has a core–halo morphology in the scenario proposed by Wood & Churchwell (1989), and its ionizing source is an O6 star (Mehring 1994). It is interesting to note that sources W51g and W51f form two extended lobes, almost symmetrical in both 6 and 20 cm radio maps, but they were not detected at 3.5 cm (Mehring 1994). No NIR counterpart was found between the lobes, nor near the peak of the radio emission of source W51f.

Instead, there is a source ~6″ W of the peak of the W51g radio emission. The offset is larger than the search radius defined in Section 2.1 (3″). Nevertheless, this target was chosen as the best NIR counterpart candidate for the UC H II region. As noted above, it turns out to be a foreground late-type star. Thus no candidate NIR counterpart has been identified for either W51g or W51f. Spitzer/IRAC images presented by Barbosa et al. (2016) show both UC H II regions W51g and W51f permeated by the extended green emission at 4.5 μm that may correspond to the ionized gas traced by the Brγ emission at 4.09 μm. The intense emission appears to be hiding the NIR sources.

4. The Spectrophotometric Distance to W51A

The spectral classification of the stellar objects associated with the UC H II regions was used to estimate their spectrophotometric distance and hence the distance to the main cluster itself. In addition, we included the objects #44, #50, #57, and #61 from Figuerêdo et al. (2008) and sources #6, #12, and #13 from Bik et al. (2019), as these sources are also members of W51A. We used the spectral types assigned by those authors, assuming all of the sources to be dwarfs (luminosity class V).

The calculation of a spectrophotometric distance d is a simple procedure that involves the classification of the objects by spectral type, the assumption of a reddening law, and the inversion of the distance modulus equation:

\[ m_K - M_K = 5 \log(d) - 5 + A_K \]  

where \( m_K \) and \( M_K \) are, respectively, the apparent and absolute K-band magnitudes of the object, \( A_K \) is the extinction in the line of sight of the source at the same wavelength, and \( d \) is the distance in parsecs.

For the spectral type assigned to each object, we used the corresponding effective temperature, absolute magnitudes, and bolometric corrections for O-type stars reported by Martins & Plez (2006). For B-type stars, we obtained the absolute magnitudes by extrapolating the relation between visual absolute magnitudes and spectral types for O stars presented by Martins et al. (2005). Then, K-band absolute magnitudes were obtained using intrinsic colors from Pecaut & Mamajek (2013), as much as their effective temperatures and bolometric corrections. In order to use a homogeneous data set, we obtained the NIR photometry and the color indices from the UKIDSS Galactic Plane Survey DR6 (Lucas et al. 2008). We adopted the extinction law presented by Damineli et al. (2016). The amount
Table 2  
Physical Parameters of Each Object in W51A and Its Spectrophotometric Distance

| Object | Spec. Type | $K_S$ (mag) | $J - H$ (mag) | $H - K_S$ (mag) | $A_K$ (mag) | log($T_{\text{eff}}$) / K | log($L_{\text{bol}}$ / $L_{\odot}$) | $d$ (kpc) |
|--------|------------|-------------|---------------|-----------------|-------------|----------------------|------------------------|-----------|
| W51a   | O8         | 10.930 ± 0.001 | 2.432 ± 0.003 | 1.354 ± 0.001 | 1.71 ± 0.03 | 4.54 ± 0.01 | 5.25 ± 0.20 | 3.59 ± 0.74 |
| W51b   | O9.5       | 11.880 ± 0.001 | 1.496 ± 0.002 | 0.858 ± 0.001 | 1.07 ± 0.03 | 4.50 ± 0.02 | 4.50 ± 0.20 | 6.17 ± 1.06 |
| W51c   | O9.5       | 12.731 ± 0.002 | 2.303 ± 0.016 | 1.978 ± 0.004 | 2.02 ± 0.36 | 4.50 ± 0.02 | 4.54 ± 0.20 | 5.89 ± 1.22 |
| W51d   | O9.5       | 12.691 ± 0.002 | 3.779 ± 0.044 | 1.755 ± 0.004 | 2.45 ± 0.11 | 4.52 ± 0.03 | 4.77 ± 0.27 | 5.06 ± 0.47 |
| W51e   | O9.5       | 13.093 ± 0.003 | 2.915 ± 0.034 | 1.874 ± 0.006 | 2.19 ± 0.16 | 4.50 ± 0.05 | 4.47 ± 0.27 | 6.44 ± 1.14 |
| #44    | O5         | 11.123 ± 0.001 | 4.676 ± 0.049 | 2.546 ± 0.002 | 3.25 ± 0.04 | 4.61 ± 0.02 | 6.07 ± 0.20 | 2.85 ± 0.59 |
| #50    | O6.5       | 12.242 ± 0.001 | 3.483 ± 0.030 | 1.981 ± 0.003 | 2.47 ± 0.07 | 4.58 ± 0.02 | 5.16 ± 0.20 | 5.65 ± 1.18 |
| #57    | O4         | 10.762 ± 0.001 | 3.926 ± 0.013 | 2.175 ± 0.001 | 2.75 ± 0.05 | 4.63 ± 0.02 | 6.07 ± 0.20 | 3.45 ± 0.72 |
| #61    | O7.5       | 12.412 ± 0.003 | ...           | 2.823 ± 0.030 | 3.67 ± 0.06 | 4.55 ± 0.01 | 5.49 ± 0.25 | 3.10 ± 0.64 |
| #6     | B1         | 12.691 ± 0.002 | 3.779 ± 0.044 | 1.755 ± 0.004 | 2.45 ± 0.11 | 4.43 ± 0.10 | 4.66 ± 0.27 | 3.87 ± 0.81 |
| #12    | B2         | 13.783 ± 0.005 | 2.140 ± 0.079 | 2.865 ± 0.022 | 2.48 ± 0.81 | 4.30 ± 0.10 | 3.91 ± 0.29 | 5.50 ± 1.44 |
| #13    | B5         | 13.766 ± 0.004 | 1.780 ± 0.014 | 1.337 ± 0.006 | 1.45 ± 0.19 | 4.19 ± 0.04 | 3.15 ± 0.27 | 6.07 ± 1.26 |
| Average|            | 4.80 ± 1.27  |               |                |             |                      |                        |           |

Note. Column (1) gives the name of the object. Column (2) gives the spectral type assigned from K-band spectra. Column (3) gives the apparent magnitude in the $K_S$ band. Column (4) gives the $J - H$ color of each object. Column (5) gives the $H - K_S$ color. Column (6) lists the amount of the extinction in the $K_S$ band, after Damineli et al. (2016). Column (7) gives the effective temperatures taken from Martins et al. (2005) and Pecaut & Mamajek (2013) for O- and B-type stars, respectively. The errors in the temperature represent an uncertainty of one spectral subtype. Column (8) gives the bolometric luminosity; the uncertainty quoted in the luminosity represents its variation based on the uncertainty in the distance to the cluster. Column (9) presents the spectrophotometric distance for each object, calculated using Equation (1), and its uncertainty represents the variation in distance due to the uncertainty in the extinction quoted in Column (6). The last row of the table presents the average distance to W51A and its standard deviation.

4.1. The New Spectrophotometric Distance to W51 Main in Context

We compare our spectrophotometric distance to W51 with the previous previous distances to the W51 complex available in the literature as summarized in Table 3, plotting them in Figure 11. The figure shows that the spectrophotometric distance derived in this work is compatible, within the uncertainties, with the near kinematic distances from Georgelin & Georgelin (1976), Crumpton et al. (1978), and Downes et al. (1980) and also the distances obtained by trigonometric parallaxes of water masers from Genzel et al. (1982), Imai et al. (2002), and Sato et al. (2010).

4.2. H-R Diagrams

Using the distance to W51A, we constructed the Hertzsprung-Russell (H-R) diagram of the cluster, considering the
extinction law of Damineli et al. (2016). We estimated the bolometric luminosity of the sources in W51A as follows. First, we corrected the apparent magnitudes for the extinction and then converted them into absolute magnitudes, scaling for the distance $d$ to the cluster presented in Table 2. After that, we applied the bolometric correction from Martins & Plez (2006) (for O-type stars) and Pecaut & Mamajek (2013) (for B-type stars). Finally, we calculated the bolometric luminosities from the absolute magnitudes. We used the bolometric luminosities and effective temperatures from Table 2 to construct the H-R diagram presented in Figure 12.

The uncertainty in the effective temperature represents the difference between the effective temperature of the assigned spectral type and the temperature of its subsequent subtype both earlier and later, leading to asymmetric upper and lower errors in most of the cases. For these sources, we considered the larger error value.

The main source of uncertainty in the bolometric luminosity of the sources arises from the uncertainty in the distance to the cluster. For this reason, the error bars in luminosity reflect the luminosities calculated taking account of the quoted uncertainty in the distance to the cluster, i.e., the upper limit corresponds to the luminosity considering the distance $d + \sigma_d$, and the lower limit was obtained using $d - \sigma_d$.

5. Discussion

In this section, we discuss the results presented in the previous sections, putting them in context and comparing them with those available in literature.

Spectrophotometric distances are critically dependent on the assumed extinction law. As such, we obtained the distance to W51 Main cluster as $d = 4.80 \pm 1.27$ kpc, including the objects previously identified by Figuerêdo et al. (2008) (after changing luminosity class from ZAMS to main sequence) and Pik et al. (2014) and adopting the extinction law from Damineli et al. (2016). Within the errors, this result is compatible with kinematic distances and distances obtained through maser parallaxes, and also reconciles with previous studies that located the region near to the tangent point of the Carina–Sagittarius arm (Kolpak et al. 2003).

Figuerêdo et al. (2008) obtained a distance to W51A of $2.40 \pm 0.4$ kpc (assuming the objects to be class V stars). The difference between their results and the results presented in this work is due to the extinction law adopted by them, Mathis (1990): $A_K = 1.7E_{H-K}$. The adoption of the Damineli et al. (2016) law results in an average extinction at $K$ of 2.3 mag compared to 3.9 mag for Figuerêdo et al. (2008) for the four stars #44, #50, #57, and #61.

A distance of about 2.50 kpc for W51A seems unlikely, and Figuerêdo et al. (2008) concluded there was no satisfactory explanation for the short distance rather than the longer kinematic and maser distances. This distance is closer than the near solution for the kinematic distance of W51A (4.3 kpc, Downes et al. 1980). Moreover, the line of sight of Galactic longitudes around $l = 49^°.5$ seems devoid of giant H II regions for distances shorter than $\approx 4$ kpc (Russeil 2003). In retrospect, the extinction law and evolved nature of the stars nicely explain the difference. Indeed our results suggest that any O star that can be observed to exhibit absorption lines is necessarily evolved from the ZAMS. This means that the timescale to clear itself from the overlying material related to its formation is similar to the time to evolve from the ZAMS for more massive stars.

The distance to W51A, calculated in Section 4.1, allowed us to further investigate the nature of the sources presented in this work. The H-R diagrams presented in Figure 12 are consistent with a young cluster still forming stars, placing sources #57 and #44 as the youngest (1.5–2.0 Myr) and as the most massive objects ($\geq 80 M_\odot$) in W51A.
Objects #61, #50, and W51a form a group of massive stars with masses ranging between 30 and 40 $M_\odot$ and ages formally between 3 and 4 Myr, but #50 is consistent with a younger age. Stars #60 and W51a are offset from the center of W51A Main/IRS1 and may indeed represent a slightly earlier epoch of star formation. A third group of objects with masses ranging between 15 and 20 $M_\odot$ and ages between 3 and 6 Myr is formed by objects W51b1, W51b2, W51c1, W51e7, and #6. The lowest mass of the objects studied in this work is that of object #12, with mass $<10 M_\odot$. Source #13 may represent an intermediate-mass ($\sim5 M_\odot$) cluster member. The ages of these objects are not constrained by our observations.

The H-R diagrams presented in Figure 12 differ from those presented by Bik et al. (2019), mainly because of the choice of the distance to the cluster and the reddening law adopted in their analysis. While we adopted 4.80 kpc and the reddening law of Damineli et al. (2016), Bik et al. (2019) used 5.39 kpc (distance modulus of 13.66) and adopted Nishiyama et al. (2009) for the extinction law.

Previous authors suggested that W51A is a very young cluster, with age 0.5–1 Myr (e.g., Goldader & Wynn-Williams 1994; Okumura et al. 2000, 2001). However, recent multi-wavelength studies (radio, Ginsburg et al. 2015; MIR, Lim & De Buizer 2019; NIR, Bik et al. 2019) and this work show that this cluster must be older. It is very difficult to assess the star formation history within such a large molecular cloud as the one W51A is embedded in. Kumar et al. (2004) suggests that, due to its location near the tangential point of the Carina–Sagittarius arm, density waves may have started the formation of stars in the cloud, discarding some internal triggering due to its large size. Clark et al. (2009) suggest that star formation in the W51 complex has been going on for the last 3 Myr at least, due to the identification of [OMN2000] LS1 as an extreme P Cygni supergiant. On one hand, Ginsburg et al. (2016b) detected dozens of massive stars still in the HC H II stage, suggesting that they may be still in the accretion phase with ages below 1 Myr and may represent the set of the youngest objects in the cluster. On the other hand, the fact there are sources that can be identified by observing their photospheric lines is an indication that there are also sources older than 1 Myr and they may represent some of the oldest objects in W51A. The coexistence of two populations with such age spread in the same cloud is an indication of an inhomogeneous star formation history.

Our data do not suggest hierarchical formation or some age/mass gradient that could favor triggering from any source. Our conclusions also support the scenario of still ongoing multi-seeded star formation.

6. Summary

We obtained medium-resolution $K$-band spectra ($R = 5200$) of a sample of eight NIR counterparts of UC H II regions (out of nine candidates) in W51A, the most active region in the massive star formation complex W51. The sample includes the NIR counterpart of W51e, the brightest source at both infrared
and radio wavelengths, according to the list presented by Mehringer (1994).

We detected photospheric lines in six sources, leading us to classify them as massive stars in the range O8–B3. When compared to the classification derived from their radio flux, we found similar spectral types, except for sources W51a and W51c1, to which we assigned a somewhat later spectral type. We could only detect nebular emission lines of H and He, often observed in embedded MYSOs, for W51e and W51e2. Typical photospheric lines of late-type stars were detected in the last object, leading us to classify it as a K7III type star, which excludes the source as the ionizing source of W51g.

We derived an average spectrophotometric distance to W51A including four O-type stars identified by Figuerêdo et al. (2008) and another three sources from Bik et al. (2019) in addition to the five massive stars identified in this work. We adopted the reddening law of Damineli et al. (2016) to estimate the extinction along the line of sight to each source. The distance obtained in this study is $d = 4.80 \pm 1.27$ kpc, in good agreement with radio kinematic distances and compatible with distances obtained by trigonometric parallaxes of masers, within the uncertainties involved. The new extinction law resolves the discrepancy of a shorter distance as derived by Figuerêdo et al. (2008).

We further analyzed the H-R diagram, showing the sample of 12 massive objects associated with W51A. The position of the sources suggests that W51A is somewhat older than previous estimates (e.g., Okumura et al. 2000, <1 Myr).

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**References**

Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Mantelet, G., & Andrae, R. 2018, AJ, 156, 58
Barbosa, C. L., Blum, R. D., Damineli, A., Conti, P. S., & Gussmão, D. M. 2016, ApJ, 825, 54
Bik, A., Henning, T., Wu, S. W., et al. 2019, A&A, 624, A63
Bik, A., Stolte, A., Gennero, M., et al. 2014, A&A, 561, A12
Blum, R. D., Barbosa, C. L., Damineli, A., Conti, P. S., & Ridgway, S. 2004, ApJ, 617, 1167
Blum, R. D., & McGregor, P. J. 2008, AJ, 135, 1708
Churchwell, E. 2002, ARA&A, 40, 27
Clark, J. S., Davies, B., Najarro, F., et al. 2009, A&A, 504, 429
Crampton, D., Georgelin, Y. M., & Georgelin, Y. P. 1978, A&A, 66, 1
Damineli, A., Almeida, L. A., Blum, R. D., et al. 2016, MNRAS, 463, 2653
Downes, D., Wilson, T. L., Bieging, J., & Wink, J. 1980, A&A, 40, 379
Ekström, S., Georgy, C., Eggenberger, P., et al. 2012, A&A, 537, A146
Fazio, G. G.,Hora, J. L., Allen, L. E., et al. 2004, ApJS, 154, 10
Figuerêdo, E., Blum, R. D., Damineli, A., Conti, P. S., & Barbosa, C. L. 2008, AJ, 136, 221
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, A&A, 616, A1
Genzel, R., Becklin, E. E., Moran, J. M., et al. 1982, ApJ, 255, 527
Georgelin, Y. M., & Georgelin, Y. P. 1976, A&A, 49, 57
Ginsburg, A., Bally, J., Battersby, C., et al. 2015, A&A, 573, A106
Ginsburg, A., Henkel, C., Ao, Y., et al. 2016a, A&A, 586, A50
Ginsburg, A., Gross, W. M., Goddi, C., et al. 2016b, A&A, 595, A27
Goldader, J. D., & Wynn-Williams, C. G. 1994, ApJ, 433, 164
Hanson, M. M., Conti, P. S., & Rieke, M. J. 1996, ApJS, 107, 281
Hanson, M. M., Kudritzki, R. P., Kenworthy, M. A., Puls, J., & Tokunaga, A. T. 2005, ApJS, 161, 154
Hanson, M. M., Luhman, K. L., & Rieke, G. H. 2002, ApJS, 138, 35
Hartmann, L., Hinkle, K., & Calvet, N. 2004, ApJ, 609, 906
Imai, H., Watanabe, T., Omodaka, T., et al. 2002, PASJ, 54, 741
Kolpak, M. A., Jackson, J. M., Bania, T. M., Clemens, D. P., & Dickey, J. M. 2003, ApJ, 582, 756
Kumar, M. S. N., Kamath, U. S., & Davis, C. J. 2004, MNRAS, 353, 1025
Lawrence, A., Warren, S. J., Almaini, O., et al. 2007, MNRAS, 379, 1599
Lim, W., & De Buizer, J. M. 2019, ApJ, 873, 1
Lucas, P. W., Hoare, M. G., Longmore, A., et al. 2008, MNRAS, 391, 136
Martins, F., & Plez, B. 2006, A&A, 457, 637
Martins, F., Schaerer, D., & Hillier, D. J. 2005, A&A, 436, 1049
Mathis, J. S. 1990, ARA&A, 28, 37
McGregor, P. J., Hart, J., Conroy, P. G., et al. 2003, Proc. SPIE, 4841, 1581
Mehringer, D. M. 1994, ApJ, 491, 713
Nishiyama, S., Tamura, M., Hatano, H., et al. 2009, ApJ, 696, 1407
Okumura, S.-i., Mori, A., Nishihara, E., Watanabe, E., & Yamashita, T. 2000, ApJ, 543, 799
Okumura, S.-i., Mori, A., Watanabe, E., Nishihara, E., & Yamashita, T. 2001, ApJ, 121, 2089
Pecaut, M. J., & Mamajek, E. E. 2013, ApJS, 208, 9
Russell, D. 2003, A&AS, 157, 333
Sacilomyer, L. K., Herriot, G., Veran, J.-P., & Fletcher, J. M. 1998, Proc. SPIE, 3353, 150
Sato, M., Reid, M. J., Brunthaler, A., & Menten, K. M. 2010, ApJ, 720, 1055
Wilson, T. L., Mezger, P. G., Gardner, F. F., & Milne, D. K. 1970, A&A, 6, 364
Wood, D. O. S., & Churchwell, E. 1989, ApJS, 69, 831
Wynn-Williams, C. G., Becklin, E. E., & Neugebauer, G. 1974, ApJ, 187, 473