

## Study of Extragalactic H ii Regions with Échelle Spectroscopy: The A2 Region in the Irregular Galaxy IC 4662 Postprint

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### Abstract

I present the results of échelle spectroscopy of a bright H ii region in the irregular galaxy IC 4662 and their comparison with results from long-slit spectroscopy of the same region. All observations were obtained with the standard spectrographs of the Southern African Large Telescope: (1) low and medium spectral resolution spectrograph Robert Stobie Spectrograph ( $R \approx 800$ ) and (2) échelle spectrograph HRS ( $R = 16,000-1,7000$ ). In both types of data the intensities of most of the emission lines were measured and abundances of oxygen and N, Ne, S, Ar, Cl and Fe were determined as well as physical parameters of the H ii region. The chemical abundances were obtained from both types of data with the Te-method. Abundances calculated from both types of data agree to within the cited uncertainties. The analysis of the échelle data revealed three distinct kinematic subsystems within the studied H ii region: a narrow component (NC,  $\sigma \approx 12 \text{ km s}^{-1}$ ), a broad component (BC,  $\sigma \approx 40 \text{ km s}^{-1}$ ), and a very broad component (VBC,  $\sigma \approx 60-110 \text{ km s}^{-1}$ , detected only in the brightest emission lines). The elemental abundances for the NC and BC subsystems were determined using the Te-method. The velocity dispersion dependence on the ionization potential of elements showed no correlation for the NC, indicating a well-mixed turbulent medium, while the BC exhibited pronounced stratification, characteristic of an expanding shell. Based on a detailed analysis of the kinematics and chemical composition, it was concluded that the BC is associated with the region surrounding a Wolf-Rayet (WR) star of spectral type WN7-8. The stellar wind from this WR star interacts with a shell ejected during an earlier evolutionary stage (either as a red supergiant or a luminous blue variable, LBV), which is enriched in nitrogen. These findings highlight the importance of high spectral resolution for detecting small-scale ( $\approx 25 \text{ pc}$ ) chemical inhomogeneities and for understanding the feedback mechanisms of massive stars in low-metallicity environments.

## Full Text

## Preamble

### Study of Extragalactic H II Regions with Échelle Spectroscopy: The A2 Region in the Irregular Galaxy IC 4662

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## Abstract

I present the results of échelle spectroscopy of a bright H II region in the irregular galaxy IC 4662 and their comparison with results from long-slit spectroscopy of the same region. All observations were obtained with the standard spectrographs of the Southern African Large Telescope: (1) low and medium spectral resolution spectrograph Robert Stobie Spectrograph ( $R \approx 800$ ) and (2) échelle spectrograph HRS ( $R = 16,000$ - $17,000$ ). In both types of data the intensities of most of the emission lines were measured and abundances of oxygen and N, Ne, S, Ar, Cl and Fe were determined as well as physical parameters of the H II region. The chemical abundances were obtained from both types of data with the Te-method. Abundances calculated from both types of data agree to within the cited uncertainties. The analysis of the échelle data revealed three distinct kinematic subsystems within the studied H II region: a narrow component (NC,  $\sigma \approx 12 \text{ km s}^{-1}$ ), a broad component (BC,  $\sigma \approx 40 \text{ km s}^{-1}$ ), and a very broad component (VBC,  $\sigma \approx 60$ - $110 \text{ km s}^{-1}$ , detected only in the brightest emission lines). The elemental abundances for the NC and BC subsystems were determined using the Te-method. The velocity dispersion dependence on the ionization potential of elements showed no correlation for the NC, indicating a well-mixed turbulent medium, while the BC exhibited pronounced stratification, characteristic of an expanding shell. Based on a detailed analysis of the kinematics and chemical composition, it was concluded that the BC is associated with the region surrounding a Wolf-Rayet (WR) star of spectral type WN7-8. The stellar wind from this WR star interacts with a shell ejected during an earlier evolutionary stage (either as a red supergiant or a luminous blue variable, LBV), which is enriched in nitrogen. These findings highlight the importance of high spectral resolution for detecting small-scale ( $\approx 25 \text{ pc}$ ) chemical inhomogeneities and for understanding the feedback mechanisms of massive stars in low-metallicity environments.

**Key words:** galaxies: abundances -galaxies: irregular -galaxies: evolution -galaxies: individual (IC 4662)

## 1. Introduction

The study of extragalactic H II regions by spectroscopy usually involves several fairly standard methods: (1) long-slit spectroscopy; (2) multi-object spectroscopy; (3) panoramic spectroscopy; (4) Fabry-Perot spectroscopy; (5) échelle spectroscopy. Each of these methods has advantages and disadvantages, and each has a specific area of application. Only panoramic and échelle spectroscopy methods can be used for the high-resolution ( $R > 10,000$ ) spectrophotometry of extragalactic H II regions in a large spectral range. In the case of panoramic spectroscopy, it is usually necessary to use several spectral configurations to cover a large spectral range, which requires stable weather conditions. This usually results in a spectral resolution of  $R \approx 5000$  (Izotov et al. 2006a; James et al. 2009, 2013a, 2013b). Two problems, limited slit length for sky spectrum subtraction and blaze correction, appear when échelle spectroscopy is used. However, both these problems can be reasonably well resolved by using a fiber échelle spectrograph.

This paper presents the possibility of the study of chemical abundances in bright extragalactic H II regions using the high-resolution échelle spectrograph at the Southern African Large Telescope (SALT; Buckley et al. 2006; O’ Donoghue et al. 2006). Such a possibility will be demonstrated by comparison of chemical abundances in a bright H II region of the galaxy IC 4662, obtained by two spectroscopic methods—long-slit and échelle.

IC 4662 is a gas rich, metal-poor, dwarf irregular galaxy at a distance of about 2.5 Mpc. It does not belong to any group and has no massive neighbors. However, the galaxy is actively star-forming and several giant H II regions are visible. The radio and infrared data show that very strong star formation is going on in the brightest H II regions which is still weakly visible in the optical (Johnson et al. 2003; Gilbert & Vacca 2009). The galaxy contains Wolf-Rayet (WR) stars (Crowther & Bibby 2009), and its star formation history has been investigated by McQuinn et al. (2009, 2010a, 2010b). van Eymeren et al. (2010) examined in detail the H I in IC 4662 and detected a giant cloud of H I around this galaxy. The first detailed analysis of the chemical abundance of the H II regions of this galaxy was done by Heydari-Malayeri et al. (1990), where it was shown that the two brightest H II regions have very similar chemical abundances. Hidalgo-Gómez et al. (2001) reported that there is a fainter H II region on the edge of IC 4662, which has a metallicity significantly different (0.5 dex) from the metallicities of the central H II region.

This article is organized as follows: Section 2 describes observations and data reduction. Section 3 briefly describes the methodology of the analysis. Section 4 presents results of our analysis, and their discussion is presented in Section 5. A conclusion is provided in Section 6.

## 2. Observations and Data Reduction

### 2.1 Long-slit Observations

The long-slit spectral observations of the H II region A2 in the galaxy IC 4662 (see Figure 1 [Figure 1: see original paper]) were carried out during SALT commissioning on 2006 April 25th with the Robert Stobie Spectrograph (RSS hereafter; Burgh et al. 2003; Kobulnicky et al. 2003), which is a spectrograph of low and medium spectral resolution. Observations were done with an image quality of 1.4 . A mosaic of three CCDs is used as the detector on the RSS, with the total mosaic size being  $6144 \times 4096$  pixels. The pixel size along the slit is 0.129" and the total slit length is 8" . A binning factor of 2 was applied during observations of IC 4662 resulting in a pixel size along the slit of 0.258" . The observations were carried out with spectral range 3650–6750 Å. The Volume Phase Holographic grating, PG900, was employed with a final reciprocal dispersion of about 0.97 Å per pixel. A slit width of 1.5" resulted in a spectral resolution of  $R \approx 800$  (FWHM  $\approx 4.8$  Å). Two 600 s exposures were made, followed by a reference spectrum of a CuAr lamp and spectral flat-fields. Zero level (bias) images were also taken for standard processing of two-dimensional (2D) spectra. In order to get the correct relative energy distribution, spectra of the spectrophotometric standard EG 21 (Hamuy et al. 1992, 1994) were obtained during astronomical twilight. SALT is a telescope with a variable pupil, so that the illuminating beam changes continuously during the observations. This makes absolute flux calibration impossible even when using spectrophotometric standards. However, the relative energy distributions are very accurate, especially as SALT has an atmospheric dispersion compensator.

The primary data reduction was done using the standard SALT pipeline (Crawford et al. 2010), and the following preliminary and spectral data reductions were done using an RSS spectral pipeline (Kniazhev 2021). For the analysis presented in this paper, a one-dimensional (1D) spectrum of the A2 region (9 pixels or 2.3") was extracted from the 2D reduced spectrum. This spectrum is displayed in Figure 2 [Figure 2: see original paper], where the most important emission lines are labeled.

### 2.2 Échelle Observations

Spectral observations of the A2 region of the galaxy IC 4662 employing the High Resolution Fiber échelle Spectrograph (HRS; Barnes et al. 2008; Bramall et al. 2010, 2012; Crause et al. 2014) were carried out on 2017 October 11. A single exposure of 2400 s duration was performed with seeing of 1.5" . The HRS is a thermostabilized double-beam échelle spectrograph, with the entire optical part housed in a vacuum to reduce temperature and mechanical influences. The blue arm of the spectrograph covers the spectral range of 3735–5580 Å, and the red arm covers the spectral range of 5415–8870 Å. The spectrograph can be used in low (LR,  $R \approx 14,000$ –15,000), medium (MR,  $R \approx 40,000$ –43,000) and high (HR,  $R \approx 67,000$ –74,000) resolution modes and is equipped with two fibers

(object and sky fibers) for each mode. During observations of the A2 region the LR mode was used with fibers of 2.23 diameter. Both CCD detectors, for the blue and red arms, were read out with a binning of  $1 \times 1$ .

All standard calibrations for HRS are done once a week, which is technically sufficient to achieve a spectral accuracy of 400–500  $\text{m s}^{-1}$  for the LR mode. The current HRS calibration plan includes: (1) three flat-field spectra to find the positions of all spectral échelle orders and correct for the effect of the brightness distribution along each échelle order (blaze correction) and (2) one (Th+Ar) lamp spectrum for wavelength calibration. Also, 11 bias images are taken at the beginning of each observational night for subsequent zero-offset accounting. Once a week, one velocity standard is observed in all modes to check the accuracy of the wavelength calibration. All velocity standards have a velocity accuracy better than 20  $\text{m s}^{-1}$  (see Kniazev et al. 2019 for details). An HRS spectrophotometric standard is observed once per month. All HRS spectrophotometric standards have spectral distributions known in steps of 3–4 Å.

The primary HRS data reduction was performed automatically using the SALT standard pipeline (Crawford et al. 2010) and the following échelle data reduction was done using the HRS pipeline described in detail in Kniazev et al. (2016, 2019). It should be noted here that the algorithm for constructing a 2D dispersion curve is the same for all HRS modes, but the optical path of the light in each mode is slightly different and the wavelength calibration result is different for different modes.

Initial and final wavelengths for each échelle order in the LR mode, the number of identified lines used and the final solution accuracy for each order are given in Tables 1 and 2 [TABLE:1, TABLE:2]. An improved version of the pipeline has been used for HRS data since 2020 September: (1) the removal of scattered light between orders has been significantly improved, and (2) stability of the wavelength extraction and calibration for the five bluer échelle orders up to wavelength 3732 Å has been improved. Thus, 41 échelle orders are now extracted and calibrated in the blue region.

FWHM measured over all lines in the reduced reference spectra was found to vary from 0.25 to 0.34 Å for the blue arm spectrum and from 0.33 to 0.53 Å for the red arm spectrum. The change in the half-width of the instrumental profile as a function of wavelength is plotted in Figure 4 [Figure 4: see original paper]. The behavior of the instrumental profile is well approximated by a first order polynomial and can be written in the form:

$$\text{FWHM} = 9.1383 \times 10^{-6} \lambda + 0.007 \text{ \AA}, \text{ for the blue spectrum in the spectral region } 3715\text{--}5580 \text{ \AA}$$

and

$$\text{FWHM} = 4.9624 \times 10^{-6} \lambda + 0.006 \text{ \AA}, \text{ for the red spectrum in the spectral region } 5415\text{--}8870 \text{ \AA}.$$

The spectral resolution  $R = \lambda/\delta\lambda$  as a function of wavelength is shown in Figure

5 [Figure 5: see original paper]. As can be seen from the figure, the resulting resolution range,  $R = 16,000\text{--}16,600$ , is slightly higher than published for the spectrograph, viz.,  $R = 14,000\text{--}15,000$ , but the difference is no more than 10%. The final échelle spectrum of the A2 region, comprising 74 spectral orders merged and corrected for the sensitivity curve, is displayed in Figure 3 [Figure 3: see original paper]. The most important emission lines visible on this spectrum are indicated.

### 3. Physical Conditions and Determination of Heavy-element Abundances

All emission lines for both types of data have been measured using programs described in detail in Kniazev et al. (2004). The programs can measure the emission line intensities in two ways: (1) as the total flux exceeding a fitted continuum at some wavelength interval and then the shape of the lines is not taken into account, or (2) by fitting a Gaussian function (or number of Gaussians) to the observed flux distribution exceeding the fitted continuum in some wavelength interval. Usually, method (1) is used except for situations when two measured lines are close to each other and their fluxes overlap and it is necessary to separate them. It is important to estimate the total measurement errors of the line fluxes as a combination of the errors: (1) errors of continuum fitting, (2) errors due to the Poisson statistics of photons in lines, and (3) errors of the spectral sensitivity curve. For the described observations the error (3) was about 2% for both types of data. All error components were summed quadratically and the total error in the line intensities was used by the programs to calculate the error of the output physical parameters and chemical composition.

The analysis of the emission spectra was carried out within the classical two-zone model of the H II region. This methodology is described in detail in Kniazev et al. (2004, 2005, 2008); Kniazev (2012). The chemical element contents of O, N, Ne, S, Ar, Cl and Fe as well as physical parameters such as the electron temperature ( $T_e$ ) and electron density ( $N_e$ ) were determined using this methodology. All the above parameters and their errors were determined taking into account the errors of the emission line intensities measured in the previous step. The spectral data for the A2 region in IC 4662 covered the whole required spectral range in both cases, although in the case of the long-slit spectra the lines of He II  $\lambda 4686$  and [N II]  $\lambda 5755$  were lost due to the gaps between the CCDs in the RSS mosaic. For this reason, two independent electron temperatures were used in the calculations based on the échelle data:  $T_e(\text{O III})$  for the hot zone and  $T_e(\text{N II})$  for the cold zone. The former was calculated from the line ratios of [O III]  $\lambda\lambda 4363, 4959, 5007$ , and the second from the line ratios of [N II]  $\lambda\lambda 5755, 6548, 6584$ . The total oxygen abundance was calculated as:

$$\text{O}/\text{H} = \text{O}^+/\text{H}^+ + \text{O}^{++}/\text{H}^+ + \text{O}^{+++}/\text{H}^+$$

In the case of the long-slit data, the cold zone temperature was calculated from an approximation based on the hot zone temperature using

equations from Izotov et al. (2006b), and the total oxygen abundance was calculated without  $O^{+++}/H$ , as this requires the presence of the He II  $\lambda 4686$  line. However, it should be noted here that the measured intensity of this line in the échelle data is less than 1% of the total flux of the H II region and, therefore, the contribution of  $O^{+++}/H$  is very small and does not exceed the accuracy of the total abundance of oxygen (Tables 3 and 4).

## 4. Results

Intensities of measured emission lines  $F(\lambda)$  reduced to intensities of the  $H\beta$  line, and the same intensities  $I(\lambda)$  corrected for interstellar absorption and underlying Balmer absorption together with the equivalent width  $EW(H\beta)$  of the  $H\beta$  emission line, the equivalent width  $EW(\text{abs})$  of the Balmer absorption lines, the extinction coefficient  $C(H\beta)$  and the extinction  $E(B - V)$  value calculated from it are presented in Table 3 for both spectra. The obtained extinction is the total extinction on the line-of-sight, being the sum of (1) the intrinsic extinction in the galaxy IC 4662, (2) the intergalactic extinction, and (3) the foreground extinction in our Galaxy. The derived electron temperatures  $T_e$  and electron densities  $N_e$ , and the calculated abundances of oxygen, nitrogen, neon, sulfur, argon, chlorine and iron are given in columns (2)-(4) of Table 4.

### 4.1 Physical Parameters and Abundances of Chemical Elements in the Long-slit and Échelle Observations

The line intensities presented in Table 3 show that two quite close but not exactly overlapping parts of the H II region A2 were apparently observed. This is obvious since in the case of the long-slit observation, a slit 1.5" wide was used, while in the case of the échelle observations a circular fiber of 2.23" in diameter was used. The image quality in both observations was very close to 1.4" and 1.5" respectively. Nevertheless, it should be noted that the intensities of most of the lines correlate quite well with each other. Exactly the same conclusion can be drawn regarding the measured equivalent width of the emission line  $H\beta$  and the estimated equivalent width of the Balmer absorption lines  $EW(\text{abs})$ , which are in good agreement with each other taking into account their errors. This agreement can be seen in the calculated temperatures, densities and chemical element abundances given in columns (2)-(4) of Table 4. The [S II] electron densities calculated from the sulfur  $\lambda\lambda 6717, 6731$  lines differ most strongly and the main reason seems to be that the line [S II]  $\lambda 6731$  is at the very edge of the long-slit spectrum (Figure 2). This could introduce an additional systematic error into its flux measurement. However, measured electron densities are so small in absolute value (and this is normal in H II regions) that even a difference of a factor of two does not result in a large difference in calculated abundances between the two spectra.

As already mentioned in Section 3, in the case of the échelle spectrum, the abundance of  $O^{+++}$  was also taken into account for the calculation of the total abundance of oxygen. This was calculated using the intensity of the He II  $\lambda 4686$  line (Kniazev et al. 2008). However, as can be seen in Table 4, the

abundance of this ion is less than 0.5% and therefore its contribution is negligibly small.

Overall, with an exposure difference of a factor of two, the échelle spectrum allows measurement of emission lines at 0.12%-0.15% of  $H\beta$  intensity with a signal-to-noise ratio about four, while in the long-slit spectrum the weakest lines are at 0.3% of the  $H\beta$  intensity with a signal-to-noise ratio about three. Of course, this is due to the difference in spectral resolution and it is quite obvious that this advantage of échelle spectroscopy will disappear quickly toward fainter objects.

To estimate the possible systematic error associated with different cold zone temperature estimates using the approximated Te(O II) temperature (Izotov et al. 2006b) for the long-slit spectrum and a direct temperature calculation Te(N II) based on line ratios [N II]  $\lambda$  5755, 6548, 6584, column (3) of Table 4 gives calculated abundances using the approximated Te(O II), and in column (4) the calculated abundances using directly calculated temperature Te(N II). The specific value of Te(O II) used in each case is highlighted in bold font in each column. It can be concluded that although, in general, elemental abundances using the directly computed temperature Te(N II) are higher, the two values are consistent to within the cited errors. Unfortunately, the intensity of the auroral line [N II]  $\lambda$  5755 is very small (0.15  $\lambda$  line) and therefore the signal-to-noise ratio for it is only about seven.

The comparison of abundances, calculated using the same methodology for two different observational methods and presented in Table 4 (columns (2) and (3)), allows us to conclude that the calculated abundances agree to within the cited uncertainties. For that reason, the HRS data can be used to study the abundances of chemical elements in bright H II regions and planetary nebulae.

## 4.2 Comparison with Previous Results

The measured extinction coefficient,  $C(H\beta)$ , as well as the extinction value  $E(B - V) = 0.68 \cdot C(H\beta)$ , in region A2 also agrees well for both types of observations with an accuracy of  $1.1\sigma$ . If we take the foreground extinction of our Galaxy in the direction of IC 4662 as 0.19-0.23 mag (Schlegel et al. 1998; Schlafly & Finkbeiner 2011), then there is almost no additional extinction in the line-of-sight outside the Milky Way. It should be noted that previous work to estimate extinction used either the Balmer line ratio  $H\gamma/H\beta$  (Hidalgo-Gómez et al. 2001) or  $H\delta$ ,  $H\gamma$  and  $H\beta$  (Crowther & Bibby 2009). Where only the  $H\delta$ ,  $H\gamma$  and  $H\beta$  lines are used to determine the extinction, the total measured value  $E(B - V) = 0.36$  mag immediately drops to  $E(B - V) = 0.16$  mag, which is in perfect agreement with the measured average extinction value of 0.162 mag for region A2 from Crowther & Bibby (2009).

Our derived abundances of oxygen and neon in the A2 region coincide within the cited uncertainties with previous estimates of abundances of these elements from Heydari-Malayeri et al. (1990); Hidalgo-Gómez et al. (2001); Crowther &

Bibby (2009). The nitrogen abundance for the region A2 was obtained earlier in Hidalgo-Gómez et al. (2001) and matches very well with the nitrogen abundance calculated from our data. Gilbert & Vacca (2009) estimated neon and sulfur content using data from Spitzer/IRS infrared spectroscopy. The abundances of these elements are slightly lower than our values, but, unfortunately, there are no errors given in that paper. If we assume that their measured abundances have errors equal to ours ( $\sigma_{el}$ , where subscript “el” refers to the particular element under discussion), then the difference does not exceed 2 to  $3\sigma_{el}$ . Also, Gilbert & Vacca (2009) point out a possible systematic shift in their abundances due to the broadening of the measured line,  $H\alpha$ , of the Humphrey series, since the intensities of all lines used by them were related to the intensity of this line.

The abundances of argon, chlorine and iron in the A2 region have been determined for the first time in our work. It is known that  $\alpha$ -elements determined from the emission spectra of H II regions are formed in massive stars. As a consequence, it is logical to assume that the abundances of these elements in H II regions are proportional to each other, and for that reason their ratios  $\log(\text{Ne}/\text{O})$ ,  $\log(\text{S}/\text{O})$ ,  $\log(\text{Ar}/\text{O})$  and  $\log(\text{Cl}/\text{O})$  should be constant. For example, the results of Izotov et al. (2006b) based on a very large sample of H II galaxies from Data Release 3 (DR3) of the Sloan Digital Sky Survey (SDSS) (Abazajian et al. 2005) indicate that this assumption is correct. As can be seen by comparing the values given in our Table 4 and the dependencies given in Izotov et al. (2006b), all the abundances of  $\alpha$ -elements determined by us, as well as their relations to the oxygen abundance, agree very well with these dependencies, which is an additional confirmation of the correctness of the abundances reported here. The iron abundance determined with the weak line [Fe III]  $\lambda$  4658 is also consistent with the relationship found in Izotov et al. (2006b) and most likely reflects the fact of iron deposition on dust particles.

### 4.3 Detected Kinematic Subsystems in the A2 Region

One of the potential features that the high spectral resolution of the échelle data provide is an ability to find and study different kinematic subsystems with different physical conditions (e.g., velocity dispersion of ionized gas and/or abundances of chemical elements) that can be seen in the studied region.

In the case of the A2 region of the galaxy IC 4662, the échelle data immediately showed the presence of three kinematic subsystems separated in velocity as well as by different velocity dispersions in the ionized gas (hereafter in the text—simply “gas dispersion”). All lines in the spectrum of region A2 with intensities greater than 3% of  $I(\text{H}\beta)$  allow us with certainty to detect the presence of two components, which in the following text will be referred to as the “narrow component” (NC) and the “broad component” (BC). The measured fluxes of the NC are about 5–7 times larger than those of the BC. An example of such components is displayed in Figure 6 [Figure 6: see original paper], where the spectral region of the  $H\alpha$  and nitrogen [N II]  $\lambda$  6548,6584 lines is shown in the upper plot and that of the sulfur doublet [S II]  $\lambda$  6716,6731 in the lower

plot.

The brightest emission lines,  $H\alpha$  and forbidden oxygen lines [O III]  $\lambda\lambda$  4959,5007, also show the presence of a third, “very broad component” (VBC hereafter; see upper panel of Figure 6), which is about 5-7 times weaker than the BC. Additionally, the VBC is found in the [He II]  $\lambda$  4686 line, and this fact will be discussed in Section 5.

In order to separate these components, each spectral line was fitted with two Gaussians (see Section 3) and no additional constraint on the decomposition was imposed. The result of this decomposition is given in Tables 5 and 6 [TABLE:5, TABLE:6]. The decomposition to components is presented only for those lines where the flux error of the BC is less than the measured BC flux itself, otherwise only the NC was considered to be visible. The  $H\alpha$  and [O III]  $\lambda\lambda$  4959, 5007 lines were fitted with three components each. The measured heliocentric velocities for all components for these components are shown in Tables 5 and 6 as well. The gas dispersion was recalculated from the measured FWHM of each component using the equation:

$$\sigma_{\text{gas}} = \sqrt{(\text{FWHM})^2 - \Delta V_{\text{instr}}^2 - \Delta V_{\text{therm}}^2}$$

where  $\Delta V_{\text{instr}}$  is the velocity correction recalculated from the instrumental FWHM correction (Equations (1) and (2) from this paper), and  $\Delta V_{\text{therm}}$  is the correction for temperature broadening, which was calculated as in Lang (1980):

$$\Delta V_{\text{therm}} = \sqrt{(2kT_{\text{e}}(\text{ion})/A(\text{ion}))}$$

where  $T_{\text{e}}(\text{ion})$  is the electron temperature of the corresponding ion from Table 4, and  $A(\text{ion})$  is the atomic weight of that ion.

Since the measurements of the emission line center have a very small formal error (only some meters per second), they are not given in Table 5, and the characteristic accuracy of radial velocity determination is taken to be the accuracy of the dispersion curve for LR échelle spectra, 300-400 m s<sup>-1</sup>.

Figure 7 [Figure 7: see original paper] shows the distribution of heliocentric velocities versus gas dispersion for the NC (blue circles), BC (red squares) and VBC (green squares) for different spectral lines. We see that the distribution of heliocentric velocities and gas dispersions indicates the presence of two, well separated, kinematic subsystems: the NC subsystem and the BC subsystem. The mean heliocentric velocity of the NC subsystem is  $V_{\text{hel}} = 300.05 \pm 2.08$  km s<sup>-1</sup>, and that for the BC subsystem is  $V_{\text{hel}} = 323.25 \pm 4.47$  km s<sup>-1</sup>. The mean gas dispersion of the NC subsystem is  $\sigma_{\text{gas}} = 11.90 \pm 2.44$  km s<sup>-1</sup>, and that for the BC subsystem is  $\sigma_{\text{gas}} = 39.97 \pm 6.85$  km s<sup>-1</sup>. It can be assumed that the real accuracy of the mean heliocentric velocity is better than the above, and an additional scatter is due to the fact that lines of different elements have slightly different heliocentric velocities. For example, the mean heliocentric velocity of the NC subsystem measured with lines of the Balmer and Paschen series only is  $V_{\text{hel}} = 300.38 \pm 0.80$  km s<sup>-1</sup> with a mean gas dispersion  $\sigma_{\text{gas}} =$

$11.60 \pm 0.71 \text{ km s}^{-1}$ . A similar picture can be seen for the VBC, where both gas dispersions and heliocentric velocities are slightly different for hydrogen and oxygen but they are very close for both oxygen lines.

Figure 8 [Figure 8: see original paper] shows the dependence of the measured gas dispersion for different emission lines as a function of the consecutive ionization energy of atoms of these elements. The upper panel displays this dependence for the NC of emission lines, and the lower panel that for the BC of emission lines. The idea behind this picture is that in the case of a central ionizing source that is losing (or has lost) some of its mass in the form of a stellar wind or of dropped shells, and because of the stratification of the ionized gas region around this source (as in the case of planetary nebulae), the outer, colder regions of the nebula (H II region) expand with higher velocities (e.g., Medina et al. 2006; Richer et al. 2008; Jacob et al. 2013).

The measured fluxes of the emission line components presented in Table 5 were used to calculate abundances of chemical elements, which are shown in columns (5) and (6) of Table 4. For uniformity, the cold zone temperature was calculated using the approximated temperature  $T_e(\text{O II})$  in both cases. The comparison shows that the calculated abundances of oxygen and nitrogen for the BC are higher than the abundances calculated for the NC and this difference is about  $3.3\sigma_{\text{el}}$  in oxygen and  $4.3\sigma_{\text{el}}$  in nitrogen. For sulfur and argon the calculated abundances for the BC are higher than those for the NC as well but these differences are less than  $1\sigma_{\text{el}}$  due to very large errors.

## 5. Discussion

An échelle spectrum of the H II region A2 in the irregular galaxy IC 4662 shows three spectral components (NC, BC and VBC), which differ in: (1) the mean velocity dispersion, (2) the average heliocentric velocity, (3) the integral flux of components in each line, (4) the abundance of chemical elements (for NC and BC only), and (5) the behavior of the measured gas dispersion for the different emission lines as a function of the sequential ionization energy (for NC and BC only).

Additionally, (1) it can be argued that both the BC and the VBC of the  $[\text{He II}] \lambda 4686$  line in terms of velocities belong to the region of the BC, since the difference in velocity for the NC  $[\text{He II}] \lambda 4686$  line ( $332.78 \text{ km s}^{-1}$ ) and the average BC velocity ( $323.25 \text{ km s}^{-1}$ ) is only  $2.1 \sigma_{\text{el}}$ ; (2) the strong line ratios used in the BPT diagrams (Baldwin et al. 1981) for both components (NC:  $\log([\text{O III}] \lambda 5007/H \lambda) = 0.72 \pm 0.01$ ,  $\log([\text{N II}] \lambda 6584/H \lambda) = -1.65 \pm 0.02$ ; BC:  $\log([\text{O III}] \lambda 5007/H \lambda) = 0.78 \pm 0.03$ ,  $\log([\text{N II}] \lambda 6584/H \lambda) = -1.52 \pm 0.03$ ) show that we are practically dealing with pure photoionization excitation.

Altogether, it can be assumed that the region generating the NC in the échelle spectrum is the main body of the H II region A2, whose gas is well mixed, and the recorded gas dispersion mainly characterizes the turbulent velocity of this

gas since its  $\sigma_{\text{gas}}$  looks practically constant in the upper panel of Figure 8. A detailed study of H I in IC 4662 (van Eymeren et al. 2010) found the systemic velocity of the galaxy to be  $V_{\text{sys}}(\text{H I}) = 302 \text{ km s}^{-1}$ , which agrees very well with the mean velocity of the NC region found from our data. The oxygen abundance we calculated for the NC (see Table 4) also agrees very well with the oxygen abundance for the same region from Crowther & Bibby (2009) (region #3 with  $\text{O}/\text{H} = 8.06 \pm 0.03 \text{ dex}$ ).

The BC is apparently formed in a separate region around young, hot stars (or just a single hot massive star), the wind from which “injects” mechanical energy into the surrounding space and encourages the expansion of the jettisoned matter enriched with chemical elements. This hot massive star (stars) is a central ionizing source for this region as well. For the BC region, the contribution of turbulent gas velocity is probably smaller than that of expansion and the expansion velocity is close to the  $\sigma_{\text{gas}}$  of the outermost region,  $50 \text{ km s}^{-1}$  (bottom panel of Figure 8).

The presence of the VBC of the He II  $\lambda 4686$  line indicates that this region is most likely associated with the presence of a WR star. Crowther & Bibby (2009) studied the H II regions A1 and A2 of the galaxy IC 4662 using images from different filters on the Hubble Space Telescope (HST) and the Very Large Telescope (VLT). In their study, they found six WR stars in these two H II regions and reported their positions. Comparison of the position of the échelle object fiber during the SALT observations (see bottom panel of Figure 1 of this paper) and the positions of WR stars detected by Crowther & Bibby (2009) (see Figure 2 of that work) affirms that the HRS fiber was placed on that part of the A2 region which contains WR star A2-WR2. The spectral aperture #3 of Crowther & Bibby (2009) included two WR stars, A2-WR2 and A2-WR3, and these authors suggested that one of those stars could be a WC star and the other a WN5–6 star. Our spectral échelle data do not show any additional lines of the WR star other than the He II  $\lambda 4686$  line. However, it should be noted here that the level of accumulated signal in the spectral region  $5800 \text{ \AA}$  is much higher than that in the blue  $4600\text{--}4700 \text{ \AA}$  region because of the overall sensitivity of the spectrograph. Since there is no indication of the presence of a broad C IV  $\lambda 5801\text{--}12$  line in the échelle spectrum, the absence of these spectral lines unequivocally confirms that the star A2-WR2 is of the WN type rather than the WC type. The measured  $\text{FWHM} = 14.31 \text{ \AA}$  for the emission line allows refinement of its ionization subclass to WN7–8 (Smith et al. 1996). The expected accuracy of such classification is approximately  $\pm 1$  subclass with a probability of 80% (Hamann et al. 2006). Additional confirmation of its classification as a late WN (WNL) star comes from the enhanced nitrogen content in the emission spectrum, which is characteristic of regions enriched by the ejecta of WNL stars.

Most of the WR stars found in Crowther & Bibby (2009) are located on the edges of the H II regions, A1 and A2. It is known that most of the studied WR stars in our Galaxy are also located outside known stellar clusters, and since most

massive stars are born in clusters (e.g., Zinnecker & Yorke 2007), it is assumed that most of the WR stars studied have been ejected from parent clusters. Such stars could be ejected either by dynamic processes in the cluster core (Poveda et al. 1967; Gies & Bolton 1986) or as a result of a supernova explosion in a close system of two massive stars (Blaauw 1961; Stone 1991). In both scenarios, the ejected WR star must be located close to the parent cluster, since the precursor WR star is a very massive star with a mass of at least  $25 M_{\odot}$ , having a lifetime of at most 5 Myr. Detailed studies of individual WR stars in our Galaxy find their inferred mother clusters based on the observed radial velocities of these stars and their proper motions (e.g., Gvaramadze et al. 2009, 2010b; Burgemeister et al. 2013). Therefore, the velocity of the NC from our study can naturally be interpreted as the velocity of the parent H II region A2, which closely matches the systemic velocity of the galaxy. In this framework, the velocity of the BC is interpreted as the velocity of the circumstellar envelope surrounding the WN star (as well as the velocity of star itself). The velocity difference,  $\Delta V \approx 23 \text{ km s}^{-1}$ , represents the radial component of the ejection velocity from the parent cluster located within H II region A2. This interpretation is further supported by the location of the WN star at the edge of H II region A2 (see the right panel of Figure 1).

Modern studies of the evolution of WR stars and their circumstellar envelopes distinguish two types of envelope. In the first case, these are compact envelopes of very young WR stars of WNL type, where the stellar wind is still confined to the region occupied by circumstellar matter dumped at a previous stage of a red supergiant (RSG) or luminous blue variable (LBV) evolution and therefore shows the signatures of CNO-processing (e.g., Chu 1981; Lozinskaya & Tutukov 1981; Gruendl et al. 2000; Gvaramadze et al. 2010a). On the other hand, winds from more evolved WR stars of WNE type interact directly with the local interstellar medium and create more extended envelopes, whose abundances of chemical elements are equal to the abundances of the surrounding H II regions (e.g., Esteban et al. 1992; Stock et al. 2011). Our analysis shows that the abundance of the chemical elements, oxygen and nitrogen, in the BC region is systematically higher than the abundance of the same elements in the NC region, which is the main body of the A2 region. This result also fits logically into the picture of ejected stellar material around a very young WN star where a fast wind has caught up with material enriched with fusion products previously shed by the RSG, and contributes to its expansion. Since its ionization subclass is WN7-8, it is quite possible that the fast WR wind is still just passing through the zone created by the slow RSG wind (Gvaramadze et al. 2009).

Let us now support the proposed ideas with various estimates based on existing models: (1) According to the models of Weaver et al. (1977) and Chevalier & Clegg (1985), the expansion velocity of a shell created by the wind of a massive star can be estimated as  $V_{\text{exp}} \approx (L_w/n)^{1/5}$ , where  $L_w$  is the mechanical luminosity of the wind, and  $n$  is the density of the surrounding medium. The mechanical luminosity of the wind can be calculated using the formula  $L_w = \frac{1}{2}M\dot{v}_{\infty}^2$ , where  $M$  is the mass-loss rate, and  $v_{\infty}$  is the terminal wind velocity.

For WR stars of type WN7-8, these parameters can be taken from Table 1 of Crowther (2007) as  $\dot{M} = 10^{-5} M_{\odot} \text{ yr}^{-1}$  and  $v_{\infty} = 1000 \text{ km s}^{-1}$ , leading to an estimated mechanical wind luminosity of  $L_w = 10^{36}-10^{37} \text{ erg s}^{-1}$ . Using the measured electron density  $n_e = 100 \text{ cm}^{-3}$ , the theoretical expansion velocity is expected to be  $30-60 \text{ km s}^{-1}$ , which is in good agreement with the measured velocity dispersion of the BC  $\approx 40 \text{ km s}^{-1}$ . (2) Since the size of the studied giant H II region is approximately 25 pc, using the average expansion velocity, the age of shell can be estimated as  $t = R/V_{\text{exp}} \approx 6 \times 10^5 \text{ yr}$ , which is consistent with the short evolutionary phase of WR stars following the RSG stage. (3) For a WN7-8 star, the typical terminal wind velocity is  $v_{\infty} = 1000-1200 \text{ km s}^{-1}$  (Hamann et al. 2006; Crowther 2007). Then, the ratio  $\sigma(\text{He II } \lambda 4686)/v_{\infty} \approx 0.3$ , which is consistent with theoretical models of line formation in WR star winds (Hillier 1991). (4) Nitrogen enrichment (a difference with a significance of  $4.4\sigma$  between NC and BC) quantitatively supports the assumption that the material was ejected during the previous RSG/LBV stage. The typical increase in nitrogen content in shells following the RSG phase is 0.2-0.4 dex (Lamers et al. 2001), which corresponds to the observed difference of 0.22 dex between NC and BC.

### 5.1 Very Broad Component

The VBC is observed in many irregular galaxies (for example, Bresolin et al. 2020; Oparin et al. 2020; Egorov et al. 2021) and is associated with the action of winds from massive stars. This component represents a unique “window” into the processes occurring in the immediate vicinity of the WR star. The extreme velocity dispersion of the VBC in the He II  $\lambda 4686 \text{ \AA}$  line is directly linked to the fast wind of the WR star and corresponds to approximately 1/3 of the expected terminal wind velocity for a WN7-8 type star (see above). Significantly lower, but still high, dispersions of the VBC in the [O III]  $\lambda 5007$  and H  $\beta$  lines (see Table 6) indicate the presence of stratification in the wind acceleration region.

The three-component structure (VBC, BC, NC) is, in essence, a direct observation of different zones in the classical wind bubble model (Weaver et al. 1977): the VBC in the He II line corresponds to the freely flowing wind zone, the VBC in the [O III]  $\lambda 5007$  and H  $\beta$  lines corresponds to the hot gas behind the shock front, while the BC corresponds to the compressed shell of cooled gas at the boundary with the surrounding interstellar medium. The relatively low intensity of the VBC (approximately 5-7 times weaker than the BC) is consistent with the small filling factor of hot gas in such a structure. The difference in radial velocities between the VBC components (Table 6) may indicate non-spherical expansion or the presence of asymmetry in the density distribution of the surrounding medium, which is consistent with modern three-dimensional models of the interaction of WR star winds with a heterogeneous medium (van Marle et al. 2011).

It should be noted that the observation of the VBC with such characteristics in

a low-metallicity environment provides valuable information about the influence of heavy-element content on stellar wind properties and their interaction with the surrounding medium. In systems with low metallicity, a decrease in both the mass-loss rate and terminal wind velocity of WR stars is expected (Vink & de Koter 2005). The presented observations show that even under such conditions, stellar wind is capable of creating a complex dynamic structure in the surrounding environment, which has important implications for understanding the feedback of massive stars in the early Universe.

## 5.2 Implications for Galaxy Evolution

In general, observations of the H II region A2 in the galaxy IC 4662 provide important information about star formation processes and feedback in low-metallicity environments: (1) The detection of significant differences in chemical composition (0.15–0.20 dex) between kinematic subsystems on a scale of only 25 pc confirms that local enrichment plays a substantial role in the chemical evolution of dwarf galaxies, contrary to the widespread belief about rapid and complete mixing of the interstellar medium in these systems. In Kniazev et al. (2005), the authors indicated that despite the established conviction that the interstellar medium in irregular galaxies is well mixed, very often information about the average metallicity of such galaxies is known with an accuracy of up to 0.3–0.4 dex, which is related both to possible processes of local enrichment and an insufficient number of quality observations. (2) The identification of an expanding shell around the WR star with increased nitrogen content demonstrates “in action” the mechanism of interstellar medium enrichment with products of massive star evolution. This is especially important for understanding the early stages of chemical evolution of the Universe, when similar processes could dominate in primordial galaxies. (3) The effective mechanical impact of the WR star wind on the surrounding environment even in low-metallicity conditions indicates that stellar feedback may be a key factor in regulating star formation in metal-poor systems. The expanding shell not only distributes enriched material, but also may create conditions for the triggered formation of the next generation of stars. (4) The discovery of the complex kinematic structure of the H II region A2 with three different components emphasizes the need to develop multiphase models of the interstellar medium in low-metallicity galaxies for adequate interpretation of observations and understanding of feedback cycles between star formation and interstellar medium properties.

## 6. Conclusions

The bright H II region A2 of the irregular galaxy IC 4662 was studied using long-slit and échelle spectroscopy at the SALT facility. This work has shown that:

1. The calculated abundances of chemical elements obtained from different spectral data are consistent with each other within the available errors, and hence the spectral data obtained from the HRS échelle spectrograph,

corrected for the spectral sensitivity curve, can be used to determine the abundances of chemical elements of emission nebulae.

2. The analysis of échelle data revealed three spectral components, apparently belonging to different subsystems of the investigated H II region. Their physical and kinematic characteristics were compared, as were the abundances of the chemical elements, oxygen, nitrogen, sulfur and argon, which were calculated using the Te method.
3. The analysis of échelle data as well as a comparison with previous studies of the region A2 in IC 4662 allowed us to suggest that one of the detected subsystems belongs to the region around a hot young WR star of WNL type, which has been ejected from the parent cluster located in the main body of region A2. The wind from this WR star “injects” mechanical energy into the surrounding area and contributes to the expansion of the envelope shed in a previous stage of evolution (RSG or LBV) and enriched with chemical elements. This assumption is very well supported by comparisons with theoretical models.

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