Ethynyl Around the HII Regions S255 and S257

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Abstract—We present the results of the ethynyl (C_2H) emission line observations towards the S255 and S257 HII regions and the molecular cloud between them. Radial profiles of line brightness, column density, and abundance of C_2H are obtained. We show that the radial profile of the ethynyl abundance is almost flat towards the HII regions and drops by a factor of two towards the molecular cloud. At the same time, we find that the ethynyl abundance is at maximum towards the point sources in the molecular cloud—the stars with emission lines or emitting in X-ray. Line profiles are consistent with the assumption that both HII regions have front and back neutral walls those move relative to each other.

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1. INTRODUCTION

Over the past 80 years, more new molecules have been discovered in the interstellar medium [1]. To date, more than 200 chemical species have been discovered in the dense and diffuse molecular clouds, apart from the atoms in different ionization degrees in the HII regions (see, for example, the list of molecules at the website of the Cologne database for molecular spectroscopy CDMS [2]; see also [3]). Complex organic molecules, such as methanol (CH_3OH), ethyleneglycol ((CH_2OH)_2), and many others, are formed by successive additions of individual atoms and radicals in the gas phase and on the surfaces of dust grains [1]. It is important that the so-called bottom-up chemistry requires reactions to occur on the surface of interstellar dust grains, which often serve as the catalysts for reactions. At the periphery of the HII regions, in the photodissociation regions (PDR), where physical and chemical processes in the interstellar medium are caused by the absorption of the ultraviolet radiation with the energy below hydrogen ionization potential (UV, from 4 to 13.6 eV), the opposite process occurs—destruction of long carbon chains, the so-called top-down chemistry [4, 5]). It is important to note that the main species—molecules and radicals—are different in the bottom-up and top-down chemistry [1]. While the initial stages of the bottom-up chemistry are fairly well understood (e.g., the chain of methanol formation from a CO molecule on the dust [6]), the starting point of the top-down chemistry and its main species are unknown, apart from the confirmed formation of fullerenes [7] as products of photodissociation of polycyclic aromatic hydrocarbons (PAH). However, it is believed that the top-down chemistry is closely related to the effect of UV radiation upon PAH, hydrocarbon grains, and long carbon chains formed in the atmospheres of red giants [8–10].

Destruction of PAHs under the action of UV radiation [11, 12] can cause interesting features in the molecular composition of the gas in PDR. For instance, in [8], a high abundance of small hydrocarbons C_2H, C_3H_2, C_4H was found toward the illuminated edge of the Horsehead nebula. Pety et al. [8] were unable to explain the hydrocarbon formation at AV = 0.1 using PDR model and suggested formation of small hydrocarbons as a result of the photodestruction of PAHs. In a later work [13], another attempt was made to simulate formation of hydrocarbons in the Horsehead nebula, considering the presence of gas and dust in the PDR at the stage of a dark cloud before the beginning of ultraviolet irradiation by the σ Ori star. Le Gal et al. [13] managed to explain the distribution of the abundance of molecules everywhere, except for the illuminated edge of the Horsehead. In [9], an excess of the abundance of l-C_3H^+ ions towards the illuminated edge of the Horsehead as compared to the results of astrochemical modeling is reported.

Interestingly, the Horsehead remains the only PDR where the abundance of small hydrocarbons has not been explained by the existing astrochemical models. In the Orion Bar PDR, close to the Orion nebula, high abundance of small hydrocarbons was explained by high-temperature chemical reactions involving
excited hydrogen molecules [14, 15]. Also, no discrepancies were found between the observed abundances of C₂H and the results of the astrochemical modeling in PDR M8 in [16]. In a recent theoretical study [17], it was shown that an effective formation of C₂H from acetylene molecules (C₂H₂) occurs as a photodestruction result of PAHs in the Orion Bar PDR. While in the Horsehead, this process is practically insignificant in comparison to the formation of C₂H by gas-phase reactions originating from ionized carbon C⁺. Experimental data on the efficiency of acetylene formation as a result of photodegradation of PAHs are contradictory. Some authors find that the products of PAH photodegradation are C and H atoms, as well as H₂ molecules (see, e.g., [18–20]).

In the infrared images obtained by space telescopes, HII regions look like ring nebulae—projections of spherical shells or ring structures onto the plane of the sky [21–23]. Despite several thousand infrared nebulae have been catalogued to date, there are no more than ten well-studied PDRs around HII regions [24, 25]. There is a lack of statistical data on the features of the size distribution of PAH particles and on the abundance of hydrocarbons in PDR. Moreover, the profiles of the molecular abundances, obtained from the ionization source deep into the molecular cloud, are required for comparison with the results of theoretical modeling.

The aim of the present study is to obtain the radial profile of the C₂H abundances in the HII regions Sh2-255 and Sh2-257 [26] (henceforth, S255 and S257) in the complex S254–S258 [27]. Entire complex is located at ≈1.78 kpc from the Sun [28]. A molecular cloud is being compressed between these two HII regions [29, 30] (see Fig. 1). Spectral types of ionizing stars of these HII regions LS 19 (S255) and HD 253327 (S257) are B0V [31] and B0.5V [30], respectively. The size of both HII regions is about 1.3 pc. The neighborhoods of S255 and S257 are active star-formation regions (see, e.g., [27, 32–34]).

2. OBSERVATIONS

In order to obtain the C₂H abundance profile in the S255 and S257 HII regions, we made observations in several selected positions along the straight lines connecting the S255 IRS1 infrared source, which is located in the molecular cloud between the HII regions (J2000 α = 06h12m54s, δ = 17°59′23″) and the ionizing stars of each of the HII regions: LS 19 (J2000 α = 06h13m04.2s, δ = 17°58′41.5″) and HD 253327 (J2000 α = 06h12m44.2′, δ = 17°59′14.3″), see Fig. 1. Observations were done from August 19 to 21, 2018 with the IRAM 30 m telescope using the EMIR 090 receiver and the FTS 50 spectrograph in the full power mode. The C₂H lines are absent in the OFF-position (J2000 α = 06h12m54.0′, δ = 18°09′23.0″) as we checked during the frequency switching mode. The beam size at the frequency of 87.4 GHz was 28″, and observations were carried out along the directions connecting S255 IRS 1 and ionizing stars, with the step of 14″. Spectral resolution was 50 kHz, which at a
frequency of 87.4 GHz corresponds to 0.17 km/s. Observations were carried out at satisfactory weather conditions, with the amount of precipitated water vapor pwv = 7–13 mm. The noise temperature of the system was at the level of 100 K. The intensity scale was converted to the temperature units of the main beam of the radiation pattern \( T_{mb} \) considering the antenna efficiency \( F_{eff} = 0.95 \), \( B_{eff} = 0.81 \). The signal accumulation time at each point was 7.7 min, which made it possible to achieve the sensitivity of 0.05 K in units of \( T_{mb} \).

The processing and analysis of spectra (considering the antenna efficiency, subtraction of the baseline, approximation of the lines by the Gaussian profiles) was done using the CLASS/GILDAS package.\(^3\)

### 3. ADDITIONAL DATA

To determine the abundance of C\(_2\)H, we used the data on the column density of the matter expressed in the number of hydrogen molecules along the line of sight \( N_{H} \) and dust temperature \( T_{dust} \), obtained as a result of processing the data from the Herschel telescope in the Hi-GAL project \(^{35}\). The processing algorithm is presented in \(^{36}\) and is applied to the objects from the Hi-GAL survey in \(^{37}\). The data themselves were taken from the open sources.\(^4\) Angular resolution of the files with spatial distribution of \( N_{H} \) and \( T_{dust} \) was 12\(^{\circ}\).

### 4. THE ANALYSIS OF OBSERVATIONAL DATA

We checked that the ratio between the brightness temperatures of the hyperfine components corresponds to the optically thin emission before the C\(_2\)H column density estimation. To do this, we checked the ratio of the brightest components at the frequencies 87328.624 MHz to 87316.925 MHz and ensured that it was in the range 0.48–0.52 (close to the theoretical 0.50) in the observed positions. The intensity ratio analysis of the multiplet lines using the CLASS \( \text{ifs} \) procedure (it assumes that the widths of all lines in the multiplet are equal) showed that the approximation procedure does not converge. This is likely due to the asymmetric line profiles (see below).

To determine the radiation concentration of the C\(_2\)H molecule \( (N_{C_2H}, \text{cm}^{-2}) \), we used the LTE assumption and the condition of optically thin emission in lines, at which expression (1) is valid. Also, we used the Rayleigh–Jeans condition \( h\nu \ll kT \), which is satisfied in observations at 3 mm.

The background radiation temperature \( (T_{bg} = 2.73 \text{ K}) \) was not considered, since its value is negligible. Thus, the column density is determined as follows (see, e.g. \(^{38}\)):

\[
N_{C_2H} = \frac{8\pi v_{ul}^2 k Q}{A_{ul} \hbar c^3} \frac{1}{g_u} \exp \left( \frac{E_u}{kT_{ex}} \right) W_{C_2H},
\]

where \( v_{ul} \) is the average weighted frequency of transition \( u \rightarrow l \) [Hz], which is computed considering line strength \( S_{ul} \) for each hyperfine component (see Table 1), \( A_{ul} \) —Einstein coefficient for spontaneous emission [1/s], \( g_u \) —statistical weight of the level, \( Q \) —statistical sum, \( E_u \) —the energy of the upper level, \( k \) —Boltzmann constant [erg/K], \( h \) —Planck constant [erg s], \( c \) —speed of light [cm/s], \( T_{ex} \) —excitation temperature of the upper molecular level, \( W_{C_2H} \) —integral intensity of the spectral line [K cm/s], \( f \) —filling factor of the telescope beam.

Einstein coefficient for entire transition \( A_{ul} \) is, in general form, given by the formula

\[
A_{ul} = \frac{64\pi^4}{3hc^3} v_{ul}^3 S_{ul} \mu^2 g_u,
\]

where \( S_{ul} = 1 \) is the strength of the transition in our case as we compute column density using the integrated intensity of the entire multiplet; \( \mu = 7.7 \times 10^{-19} \) (0.77 D) is the dipole moment of the molecule in CGS units.

Substituting (2) into (1), we obtain the following expression for estimating column density \( N_{C_2H} \):

\[
N_{C_2H} = \frac{3k}{8\pi^3 v_{ul}^2} \frac{Q}{f} \exp \left( \frac{E_u}{kT_{ex}} \right) W_{C_2H}.
\]

All the parameters in (3), excluding the product \( Q \exp(E_u/(kT_{ex}))W_{C_2H} \), only depend on the transition type and the structure of a molecule.

The value of \( Q \) depends on the excitation temperature \( T_{ex} \), while \( W_{C_2H} \) is determined from observations. For each observed position, we computed \( Q \) from the

### Table 1. The parameters of hyperfine components of the 1 → 0 transition of C\(_2\)H molecule according to CDMS

| Transition   | Frequency, MHz | \( E_{ul}/k \), K | \( g_u \) | \( S_{ul} \) |
|--------------|---------------|-------------------|--------|-----------|
| \( 1_{3/2,1} \leftarrow 0_{1/2,1} \) | 87284.156     | 4.2               | 3      | 0.17      |
| \( 1_{3/2,2} \leftarrow 0_{1/2,1} \) | 87316.925     | 4.2               | 5      | 1.66      |
| \( 1_{3/2,1} \leftarrow 0_{1/2,0} \) | 87328.624     | 4.2               | 3      | 0.83      |
| \( 1_{1/2,1} \leftarrow 0_{1/2,1} \) | 87402.004     | 4.2               | 3      | 0.83      |
| \( 1_{1/2,0} \leftarrow 0_{1/2,1} \) | 87407.165     | 4.2               | 1      | 0.33      |
| \( 1_{1/2,1} \leftarrow 0_{1/2,0} \) | 87446.512     | 4.2               | 3      | 0.17      |

\(^2\) http://www.iram.es/IRAMES/mainWiki/Iram30mEfficiencies.

\(^3\) Continuum and Line Analysis Single-Dish Software http://www.iram.fr/IRAMFR/GILDAS.

\(^4\) http://www.astro.cardiff.ac.uk/research/ViaLactea/.
adopted $T_{\text{ex}}$ value, using an expression for linear molecules:

$$Q = \frac{k T_{\text{ex}}}{h B_0} + \frac{1}{3}.$$  

(4)

where $B_0 = 43674.534 \times 10^6$ s\(^{-1}\) is the rotational constant for the molecule.

We took the dust temperature as the excitation temperature. Then, on the map of the dust temperature distribution, regions with a diameter of 28″ were selected, with the centers corresponding to the positions in which the observations were carried out (see Fig. 1) and the dust temperature was averaged over the size of the position. The standard deviations from the mean value were used as the uncertainty of the temperature $T_{\text{dust}}$ (and $T_{\text{ex}}$, see below). Below, we discuss a possible inconsistency between the dust temperature and the excitation temperature for the C\(_2\)H(1–0) transition.

Abundance of the molecules ($x_{C_2H}$) was determined relative to the column density of the hydrogen nuclei:

$$x_{C_2H} = \frac{N_{C_2H}}{2N_{H_2}}.$$  

(5)

The values of integral intensity $W_{C_2H}$ were determined as an integral of the brightness temperature $T_{mb}$ over velocity during the analysis of the emission spectra of the molecule using CLASS. Results are presented in Section 5.

5. RESULTS

According to the observation results in twenty studied positions, six hyperfine components of the ethynyl J = 1–0 transition were detected in the spectra. The spectrum of the entire hyperfine structure at the position 10 is shown in Fig. 2, while four brightest hyperfine components at all positions are shown in Fig. 3. The brightest lines were found at positions 8–12 in the direction to the molecular cloud. In the direction toward the ionizing star LS 19 in S255 (position 1), the hyperfine components (at frequencies $\nu = 87284.156$ MHz and $\nu = 87445.512$ MHz) are poorly determined. In the direction toward HD 253327 (position 18), only the brightest components of the hyperfine structure are visible. The parameters of the ethynyl emission lines are listed in Table 2. Line profiles are asymmetric, they differ from Gaussian ones by a higher intensity on the red side (see, for example, the spectra at positions 2–4 and 13 close to the directions to the ionizing stars). Flat line profiles are also observed (for instance, positions 3 and 14). The profile shapes of the hyperfine components can be different at the same position. The line profiles are symmetric in the central positions 8–12. The line widths in the directions to the ionizing stars ($\Delta \nu = 3.5 \pm 0.17$ km/s in the position 1; $\Delta \nu = 5.12 \pm 0.71$ km/s in the position 18) are 1.5–2 times higher than the line widths towards the molecular cloud ($\Delta \nu = 2.37 \pm 0.17$ km/s at the position 10). It can be seen that the line peak towards the molecular cloud ($\nu = 7.31$ km/s) is located at the dip between the peaks in the directions to the ionizing stars (for example, at positions 2, 3, 5, 14, 17, and 18, peaks at the velocities $\approx 5.5$ and 8.2 km/s). The distance between the peaks in the positions where the profiles are two-peaked is approximately 1–1.5 km/s. It is important to note such a difference in velocities corresponds to the characteristic expansion rate of the spherically-symmetric HII regions (see, e.g., [39, 40]). All this indicates the presence of several kinematic components along the line of sight near the ionizing stars. Apparently, these are the front and rear molecular walls of the HII regions, which contribute to the formation of blended compo-

Fig. 2. Emission spectrum of the C\(_2\)H molecule upon 1 $\rightarrow$ 0 transition in the temperature scale of the main lobe for position 10.
ments with close velocities. Examples of "position–velocity" diagrams for expanding envelopes around star-forming complexes with several HII regions can be found in [41, 42]. Despite the quantitative difference between the characteristic expansion rates of star-forming complexes and HII regions around single stars, the qualitative picture is similar (see also [43]).

As mentioned above, for the value of the studied positions, we used . The values of are listed in Table 2 and shown in Fig. 4a. It can be seen that the excitation temperature reaches its maximum value of \( K \) at the central position 10 (direction to S255 IRS 1 in the molecular cloud) and then decreases at most by 5 K in the direction of the ionizing stars. The value of has a maximum in the direction to S255 IRS 1 (see Table 2). Radial profiles of and are shown in the upper panels of Fig. 4. They have similar appearance with a maximum in the position 10 and a gradual decrease towards both the ionizing stars. The fact that \( N_{\text{H}_2} \) does not decrease to zero in the positions 1 and 18 indicates the presence of neutral gas in the directions to the ionizing stars. This is consistent with the conclusions about the front and rear walls of the HII regions made above.

The values of column density and the abundance of ethynyl are presented in Table 3 and shown in the lower panels in Fig. 4. The radial profile of \( N_{\text{C}_2\text{H}} \) has the same shape as that of \( N_{\text{H}_2} \). The maximum column density of \( \text{C}_2\text{H} \) molecules is reached in the position 10: \( N_{\text{C}_2\text{H}} = (1.78 \pm 0.91) \times 10^{14} \text{ cm}^{-2} \). In the directions to the positions 1 and 18, the column density of ethynyl decreases by an order of magnitude in S255 and 25 times in S257.

Having determined the value of \( N_{\text{C}_2\text{H}} \) under assumption of LTE, we checked the closeness of the LTE and non-LTE estimates. For that purpose, we used the RADEX package, which allows estimating the brightness of the emission lines in the non-LTE model for given parameters of the medium: temperature, density, and column density of molecules [44]. To perform this comparison, we adopted the dust temperature as the kinetic temperature along with the observed line widths and our LTE-based estimates for . Since we have no information on the gas density spatial distribution in the molecular cloud, we checked the brightness of the theoretical spectra for several density values, namely \( 10^2, 10^3, \) and \( 10^4 \text{ cm}^{-3} \). For the central positions in the direction to the molec-

| Position | \( \nu^*, \text{ km/s} \) | \( \Delta \nu^*, \text{ km/s} \) | \( T_{\text{peak}}, \text{ K} \) | \( W_{\text{C}_2\text{H}}, (\text{K km})/\text{s} \) |
|----------|----------------------------|-----------------------------|-----------------------------|----------------------------------|
| 1        | 7.59 \( \pm \) 0.17       | 3.43 \( \pm \) 0.17         | 0.33 \( \pm \) 0.02         | 2.98 \( \pm \) 0.36              |
| 2        | 8.24 \( \pm \) 0.17       | 3.08 \( \pm \) 0.17         | 0.36 \( \pm \) 0.03         | 3.45 \( \pm \) 0.39              |
| 3        | 8.24 \( \pm \) 0.17       | 2.90 \( \pm \) 0.17         | 0.42 \( \pm \) 0.03         | 3.32 \( \pm \) 0.38              |
| 4        | 8.06 \( \pm \) 0.17       | 2.63 \( \pm \) 0.17         | 0.50 \( \pm \) 0.03         | 3.47 \( \pm \) 0.33              |
| 5        | 7.59 \( \pm \) 0.17       | 3.07 \( \pm \) 0.17         | 0.62 \( \pm \) 0.04         | 4.89 \( \pm \) 0.50              |
| 6        | 7.28 \( \pm \) 0.17       | 2.73 \( \pm \) 0.17         | 0.81 \( \pm \) 0.04         | 5.68 \( \pm \) 0.51              |
| 7        | 7.30 \( \pm \) 0.17       | 2.09 \( \pm \) 0.74         | 1.49 \( \pm \) 0.03         | 8.18 \( \pm \) 0.65              |
| 8        | 7.47 \( \pm \) 0.17       | 2.12 \( \pm \) 0.17         | 2.63 \( \pm \) 0.06         | 15.09 \( \pm \) 1.16             |
| 9        | 7.45 \( \pm \) 0.17       | 2.19 \( \pm \) 0.17         | 3.29 \( \pm \) 0.06         | 19.80 \( \pm \) 0.99             |
| 10       | 7.31 \( \pm \) 0.17       | 2.37 \( \pm \) 0.17         | 3.66 \( \pm \) 0.11         | 24.46 \( \pm \) 1.85             |
| 11       | 7.32 \( \pm \) 0.17       | 2.33 \( \pm \) 0.17         | 3.86 \( \pm \) 0.08         | 25.23 \( \pm \) 1.81             |
| 12       | 7.46 \( \pm \) 0.17       | 2.41 \( \pm \) 0.17         | 2.45 \( \pm \) 0.07         | 16.95 \( \pm \) 1.26             |
| 13       | 7.55 \( \pm \) 0.17       | 3.02 \( \pm \) 0.17         | 0.77 \( \pm \) 0.04         | 6.09 \( \pm \) 0.52              |
| 14       | 7.21 \( \pm \) 0.17       | 3.47 \( \pm \) 0.17         | 0.33 \( \pm \) 0.02         | 2.82 \( \pm \) 0.37              |
| 15       | 7.25 \( \pm \) 0.17       | 3.33 \( \pm \) 0.19         | 0.21 \( \pm \) 0.02         | 2.16 \( \pm \) 0.32              |
| 16       | 7.14 \( \pm \) 0.17       | 3.77 \( \pm \) 0.34         | 0.16 \( \pm \) 0.01         | 1.49 \( \pm \) 0.43              |
| 17       | 6.52 \( \pm \) 0.23       | 4.27 \( \pm \) 0.58         | 0.10 \( \pm \) 0.01         | 1.43 \( \pm \) 0.43              |
| 18       | 6.50 \( \pm \) 0.29       | 5.12 \( \pm \) 0.71         | 0.07 \( \pm \) 0.01         | 1.02 \( \pm \) 0.30              |
| 19       | 6.57 \( \pm \) 0.50       | 4.12 \( \pm \) 1.01         | 0.06 \( \pm \) 0.01         | 0.24 \( \pm \) 0.25              |
| 20       | 5.93 \( \pm \) 0.31       | 4.11 \( \pm \) 0.72         | 0.06 \( \pm \) 0.02         | 0.44 \( \pm \) 0.22              |

The parameters marked by an asterisk (*) are determined using the hfs method, which considers them to be equivalent to a single Gaussian with different levels of relative intensity. The peak intensity was determined for the brightest component at the frequency \( \nu = 87316.925 \text{ MHz} \) using the gauss method. The integrated intensity is determined for all components of the multiplet.

According to Table 3, the values of the column density of ethynyl are comparable with the values of the column density of \( \text{C}_2\text{H} \). The values of the column density of ethynyl are also comparable with the values of the column density of \( \text{C}_2\text{H} \). The maximum column density of \( \text{C}_2\text{H} \) molecules is reached in the position 10: \( N_{\text{C}_2\text{H}} = (1.78 \pm 0.91) \times 10^{14} \text{ cm}^{-2} \). In the directions to the positions 1 and 18, the column density of ethynyl decreases by an order of magnitude in S255 and 25 times in S257.

Having determined the value of \( N_{\text{C}_2\text{H}} \) under assumption of LTE, we checked the closeness of the LTE and non-LTE estimates. For that purpose, we used the RADEX package, which allows estimating the brightness of the emission lines in the non-LTE model for given parameters of the medium: temperature, density, and column density of molecules [44]. To perform this comparison, we adopted the dust temperature as the kinetic temperature along with the observed line widths and our LTE-based estimates for \( N_{\text{C}_2\text{H}} \). Since we have no information on the gas density spatial distribution in the molecular cloud, we checked the brightness of the theoretical spectra for several density values, namely \( 10^2, 10^3, \) and \( 10^4 \text{ cm}^{-3} \). For the central positions in the direction to the molec-
Fig. 3. Emission spectra of the C$_2$H molecule in the four brightest components of the hyperfine structure of the 1 → 0 transition in the temperature scale of the main lobe. The numbers show the positions corresponding to Fig. 1.
ular cloud, we obtained agreement of the observed brightness with the LTE model within 10% of the observed intensities for the density of $10^4 \text{ cm}^{-3}$; this density is reasonable in the molecular clouds. For the points in the directions of the ionizing stars, the theoretical non-LTE values of the brightness temperatures are significantly (up to an order of magnitude) lower than those observed at the densities from $10^2–10^3 \text{ cm}^{-3}$ (reasonable values of the density when moving toward the star from the molecular cloud). As well, the excitation temperature of ethynyl radiation is lower than the kinetic temperature in the RADEX calculations.

To obtain the observed line brightness, we need to increase $N_{\text{C}_2\text{H}}$ by an order of magnitude. On the other hand, in the non-LTE simulation with the density of $10^4 \text{ cm}^{-3}$ brightness of hyperfine components is reproduced within 10%, which also may hint at the presence of dense foreground and background molecular walls of the HII regions. Excitation temperatures, obtained in the non-LTE case, are 4–6 K. This means that ethynyl lines are excited in subthermal regime. As column density is only weakly dependent on excitation temperature at 3 mm, varying $T_{\text{ex}}$ from 4–6 K to 25 K, we obtain results that differ within a factor of 3. To narrow down the parameter range for non-LTE modelling, it is necessary to carry out additional observations of ethynyl lines corresponding to other transitions.

Considering the obtained dependence of the ethynyl abundance, the following features can be noted: the values of the abundance at positions 1–8 (in the direction toward the star LS 19 in S255) and 13–18 (toward the star HD 253327 in S257) show tendency to increase in comparison with positions 9–12 in the molecular cloud. Thus, in the direction to the molecular cloud, in the position 10, the abundance is $x_{\text{C}_2\text{H}} = (5.83 \pm 5.07) \times 10^{-9}$, while in the direction to the ionizing stars (positions 1 and 18) $x_{\text{C}_2\text{H}} = (13.91 \pm 2.47) \times 10^{-9}$ and $x_{\text{C}_2\text{H}} = (9.60 \pm 2.83) \times 10^{-9}$, respectively. A large error in determination of the ethynyl abundance toward the molecular cloud (for example, at position 11 $x_{\text{C}_2\text{H}} = (10.18 \pm 13.81) \times 10^{-9}$) is due to the fact that, at the positions over which the value $N_{\text{H}_2}$ is averaged, there are several bright spots on the distribution map of $N_{\text{H}_2}$. For this reason, the standard deviation in the positions 8–11 is higher than in other positions. Nevertheless, we clearly see the factor of 2 decrease in the ethynyl abundance in the direction to the molecular cloud in comparison with rather flat areas of the radial profile in the direction to the HII regions. The flat parts of the abundance profile suggest that the HII regions are surrounded by quasispherical molecular shells in which ethynyl is distributed almost uniformly.

Table 3. The calculation results of the column density and abundance of ethynyl

| Position | $Q$  | $T_{\text{ex}}$, K | $N_{\text{H}_2}$, $10^{20}$ cm$^{-2}$ | $N_{\text{C}_2\text{H}}$, $10^{14}$ cm$^{-2}$ | $x_{\text{C}_2\text{H}}$, $10^{-9}$ |
|----------|------|-------------------|---------------------------------|---------------------------------|-----------------|
| 1        | 12.4 | 25.3 ± 0.3        | 47.6 ± 6.2                     | 1.33 ± 0.16                    | 13.91 ± 2.47    |
| 2        | 12.4 | 25.3 ± 0.2        | 55.3 ± 3.6                     | 1.53 ± 0.17                    | 13.87 ± 1.81    |
| 3        | 12.3 | 25.0 ± 0.2        | 56.1 ± 7.6                     | 1.47 ± 0.17                    | 13.06 ± 2.32    |
| 4        | 12.2 | 24.8 ± 0.1        | 56.7 ± 17.4                    | 1.52 ± 0.14                    | 13.43 ± 4.32    |
| 5        | 12.2 | 24.8 ± 0.2        | 72.9 ± 31.2                    | 2.15 ± 0.22                    | 14.72 ± 6.48    |
| 6        | 12.2 | 24.9 ± 0.2        | 93.5 ± 44.7                    | 2.50 ± 0.22                    | 13.37 ± 6.50    |
| 7        | 12.2 | 24.9 ± 0.7        | 162.2 ± 71.2                   | 3.60 ± 0.29                    | 11.10 ± 4.95    |
| 8        | 11.7 | 23.9 ± 1.3        | 436.6 ± 365.2                  | 6.48 ± 0.50                    | 7.42 ± 6.23     |
| 9        | 12.6 | 25.7 ± 3.5        | 780.9 ± 483.2                  | 8.89 ± 0.49                    | 5.69 ± 3.54     |
| 10       | 14.0 | 28.6 ± 2.7        | 1011.0 ± 877.0                 | 11.78 ± 0.91                   | 5.83 ± 5.07     |
| 11       | 12.7 | 25.9 ± 2.1        | 559.3 ± 758.1                  | 11.38 ± 0.83                   | 10.18 ± 13.81   |
| 12       | 12.4 | 25.2 ± 0.6        | 159.9 ± 65.1                   | 7.52 ± 0.56                    | 23.50 ± 9.73    |
| 13       | 12.5 | 25.5 ± 0.4        | 75.7 ± 27.7                    | 2.72 ± 0.23                    | 17.97 ± 6.75    |
| 14       | 12.5 | 25.5 ± 0.6        | 48.5 ± 10.5                    | 1.26 ± 0.17                    | 12.99 ± 3.29    |
| 15       | 12.3 | 25.1 ± 0.4        | 38.0 ± 6.0                     | 0.96 ± 0.14                    | 12.57 ± 2.72    |
| 16       | 12.1 | 24.6 ± 0.2        | 30.6 ± 2.4                     | 0.65 ± 0.19                    | 10.64 ± 3.18    |
| 17       | 11.8 | 24.1 ± 0.4        | 25.5 ± 3.0                     | 0.62 ± 0.19                    | 12.10 ± 3.91    |
| 18       | 11.7 | 23.8 ± 0.2        | 22.8 ± 0.6                     | 0.44 ± 0.13                    | 9.60 ± 2.83     |
| 19       | 11.7 | 23.8 ± 0.3        | 24.0 ± 1.4                     | 0.10 ± 0.11                    | 2.12 ± 2.23     |
| 20       | 11.5 | 23.4 ± 0.5        | 26.6 ± 1.7                     | 0.19 ± 0.09                    | 3.53 ± 1.77     |
6. DISCUSSION

For the efficient formation of ethynyl, it is necessary to have C$^+$ ion and molecular hydrogen H$_2$ (see [45–47]) in the gas-phase; these conditions are satisfied in the PDRs. In the molecular cloud, carbon is contained mainly in the CO molecules due to the weakening of the radiation field of the star by the dust and shielding by H$_2$ molecules. Therefore, the decrease in the abundance of ethynyl in the molecular cloud at positions 7–13 is easily explained by the conversion of carbon into CO. Approximately equal abundance of ethynyl in the directions to the HII regions indicates that their chemical evolution proceeds in a similar way. This is not surprising, since these HII regions are ionized by stars of practically the same spectral type and have the same size. The increase of the ethynyl abundance by a factor 1.5–2 at positions 12 and 13 does not exceed the scatter within the errors in the value determination. Note that point sources are seen in the visual (Fig. 1) and IR images of 2MASS in the directions at positions 12–13. In particular, the region corresponding to the position 12 contains a star with emission lines S255 1, with observed emission in the H$\alpha$ line [48] (bright points are visible in Fig. 1 at positions 12 and 13) and a Herbig–Haro object S235 H1 [49]. Nearby X-ray source CXOU J061250.6 + 175909, a young low-mass star in the S255–IR cluster, is located [50] there. It is quite possible that the ionizing radiation in the vicinity of these point sources leads to a local increase of the ethynyl abundance due to the ionization of carbon-containing molecules with the release of the C$^+$ ion, which takes part in the chemical chains of ethynyl formation. The radial profile of the ethynyl abundance is featureless in the directions to the ionization front (positions 6 and 16 for S255 and S257, respectively). To positions with the dust temperature of 23–25 K corresponds to a UV field with $G_0 = 50–100$ in units of the Habing field (see, for example, [51]).

The value of $G_0$ in S255–S257 is close to that found in the Horsehead PDR, so it is necessary to perform additional observations of other ethynyl emission lines to obtain accurate radial profiles of its abundance and to compare ethynyl abundances at the ionized edge of the Horsehead PDR and in the vicinity of the ionization front in S255–S257.

Fig. 4. The profiles of the physical parameters: dust temperature, also $T_{\text{ex}}$ (a), column density of $N_{\text{H}_2}$ (b), column density of ethynyl (c), and abundance of ethynil (d).
The data of observations of C$_2$H (4–3) in the direction of S255 IRS1 (the central position 10 in this study) by ALMA are presented in [34] and column density of ethynyl is estimated there. Despite the difference in the scale, the estimates agree within a factor of 5 (our estimate is lower), indicating that the ethynyl is contained in dense molecular cloud.

Comparison of the column density of ethynyl in the vicinity of S255–S257 with the values found in other PDRs showed that the values in the directions to the HII regions are similar to those found in the Horsehead, IC 63 [52], and M 8 [16]. As we approach the peak of the gas column density in the molecular cloud, the values of $N_{\text{C}_2\text{H}}$ approach the values observed in the Orion Bar PDR [15] and some other molecular clouds (see, e.g., [53, 54]), while the maximum observed values of $N_{\text{C}_2\text{H}}$ in the positions 10 and 11 are comparable to these in PDR and molecular cloud OMC-1 [55] (see also Fig. 10 in [54]). The abundance of ethynyl at the radial profile is similar to the value observed in the Orion Bar PDR: according to the estimates from [15], the abundance in the interval (0.7–2.7) $\times$ 10$^{-8}$ in an object with the radiation field $G_0 \sim 10^4$ can be explained using high-temperature chemical reactions with excited molecular hydrogen. Thus, the PDR in S255–S257 is interesting for astrochemical modeling, because a comparable abundance of ethynyl is observed for $G_0$ lower by two orders of magnitude in comparison with the Orion Bar PDR.

7. CONCLUSIONS

To summarize the study, we draw the following conclusions:

(1) We made observations of the C$_2$H molecule in the HII regions S255 and S257 at twenty positions along the straight lines connecting the IR source S255 IRS1 located in the molecular cloud with ionizing stars in each of the regions: LS 19 and HD 253327.

(2) The brightest emission of ethynyl molecules is observed towards the molecular cloud (brightness temperature $\approx$ 4 K), the weakest one – towards the ionizing stars ($<$ 0.5 K). The largest line widths are found towards the ionizing stars ($= 3$–$5$ km/s), the smallest ones – in the direction toward the molecular cloud between the HII regions ($= 2$ km/s). The shape of the line profiles indicates that several kinematic components exist in the molecular envelope. The components can be separated along the line of sight near the ionizing stars. These components can be the front and rear walls of the HII regions.

(3) In twenty studied positions, we determine the column densities and the abundances of ethynyl. The maximum value of the column density $= 12 \times 10^{18}$ cm$^{-2}$ is found toward the center of the molecular cloud; it decreases in both directions toward the ionizing stars. The minimum abundances, on the contrary, are found in the direction to the molecular cloud ($6 \times 10^{-9}$), while the abundance is about two times higher in the directions to the ionizing stars. It is shown that the C$_2$H abundance is at maximum and attains $2 \times 10^{-8}$ in the direction of point sources in the molecular cloud – stars with emission lines or X-ray sources.

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